Impacts of installation of an oil pipeline on the productivity of Ontario cropland

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CONCLUSIONS

Measurements of field-crop yields and soil properties of land traversed by the Sarnia-Montreal oil pipeline indicated that pipeline installation detrimentally affected both crop yields and soil physical and chemical properties. Soil mixing and compaction on the right-of-way were prevalent on medium to fine textured soils. Compaction did not appear to be a problem at one coarse textured site. Soil chemical data indicated that spoil from the trench was spread across the right-of-way at most sites. This practice should be avoided. Reduced soil organic matter levels in the right-of-way adversely affected both nitrogen status and soil tilth. Medium to fine-textured right-of-way soils had reduced porosities and hydraulic conductivities, and increased strengths compared with undisturbed adjacent soils. Construction of pipelines should be undertaken on dry soils (June-September) or on soil frozen to a depth of 20 cm, if deleterious impacts to agricultural land are to be avoided. Stripping of topsoil from the trench, but not the work area may be beneficial in reducing adverse impacts.

SUMMARY OF FINDINGS

Monitoring of field crop yield and quality at selected sites along the Sarnia-Montreal oil pipeline revealed that:

- yields on the right-of-way of the Lambton County sites were reduced by almost 50% for the first two years after installation. Smaller, but significant yield reductions were still apparent at some sites in 1979, the fourth year after installation.
- silage corn yields in Eastern Ontario were reduced by about 40% in 1977, the first cropping year after installation.
- Midsummer plant height reductions on the right-of-way were found to be a reliable indicator of grain corn and soybean reductions for that season.
- differences in midsummer corn and soybean heights between the right-of-way and adjacent fields averaged about 55% in 1976 and about 25% in 1979, indicating considerable improvements in the right-of-way yields over this period. Small grain height differences remained essentially unchanged between 1976 and 1979.
- nutrient contents of crops were only marginally affected by pipeline installation although maturity (particularly of silage corn) may have been delayed at some sites.

Chemical analysis of soil samples from the yield sites revealed considerable mixing of surface and subsurface soil layers both over the trench and in the work area. In the 0-15 cm layer, organic matter levels, total N and cation exchange capacities were lower over the trench and in the work area compared with undisturbed adjacent soils. Soil test P and

K levels tended to be somewhat lower on the right-of-way than adjacent fields. Also indicative of soil mixing were the higher pH and carbonate concentrations on the right-of-way. However, these were not sufficiently high to affect productivity. Soil organic matter and total N contents tended to be higher in the 15-30 cm layer of the work area than those at the same depth in adjacent undisturbed land. This may have been due to spreading of subsoil from the trench over the topsoil of the right-of-way. Rutting from vehicles may have contributed to soil mixing in the work area.

Determination of selected soil physical properties indicated that:

- bulk densities and cone index (penetrometer resistance) values were consistently higher on the right-of-way while saturated hydraulic conductivities were lower on the right-of-way at the Lambton county sites compared with adjacent undisturbed fields. Data indicated that pipeline installation resulted in reduced total porosity and hence lower rates of water transmissibility.
- soil water desorption curves for the most adversely affected Brookston site indicated that pipeline installation reduced not only total porosity, but also water holding capacity. Porosity changes on the right-of-way may have been due to soil mixing as well as to compaction.
- greater resistance to penetration (cone index) on the right-of-way increased strength of the right-of-way may have been due to altered water holding and transmission properties caused by disturbance.

- clay contents of surface horizons increased at Lambton Co. sites where undisturbed soils consisted of lighter-textured surface horizons underlain by heavier-textured parent materials.
- pipelining had no effect on either bulk densities or hydraulic conductivities of the construction zones at a sandy Durham region site.

Construction of a 30 cm oil pipeline under relatively good weather conditions in the fall of 1977 resulted in both decreased total and drainable porosities of a Haldimand clay.

Data from the Canadian Soil Information System (CanSIS) were analyzed and equations developed relating plasticity and compactability properties of Quebec and Ontario soils to organic C and particle size distributions.

Greenhouse studies indicated that the reduced soil organic N contents in right-of-way soils justified increasing recommended N fertilization rates. Fertilizer trials in the greenhouse using surface soils taken from a right-of-way subjected to pipelining under frozen (winter) and from the Sarnia-Montreal fall right-of-way (unfrozen, wet) were also conducted. Yields of corn grown on winter constructed right-of-way soils matched those grown on adjacent undisturbed soil if provided with sufficient fertilizer amendments. Fertilizer could not eliminate yield reductions on fall construction right-of-way soils.

1. INTRODUCTION

Construction of the Sarnia-Montreal oil pipeline in the period September 1975 to March 1976, provided an opportunity to assess some effects of the process on the productivity of Ontario soils. This pipeline runs adjacent to two previously constructed pipelines from Sarnia to Port Credit, a distance of 330 km. The original Sarnia-Port Credit line was constructed in the summer and fall seasons of 1956 and 1957. Various loops of this line were installed in the summers of 1967, 1971 and 1973. The steel pipe used in the Sarnia-Montreal pipeline was 76.2 cm in diameter and had a wall thickness varying from 0.59 to 0.65 cm. Construction was carried out by different subcontractors in each of seven "spreads" which extended a total distance of 842 km from Sarnia to Montreal.

The right-of-way for construction of the pipeline was 18.3 m in width. Soil disturbance occurred during the digging of the trench and from the heavy traffic transporting pipe to the area, adjacent to the trench. This latter area is designated as the "stringing" or work area. The "spreads" are shown in Figure 1 which gives the location of the pipeline.

Pipeline construction was expected to affect soil productivity in various ways; by creating weed problems, by disruption of tile drainage systems, by soil compaction and by loss of topsoil or mixture with subsoil. The purpose of this investigation was to assess the effect of the construction on crop yields and on chemical and physical soil properties. The detrimental effect of soil compaction on soil productivity has been recognized and the subject reviewed (Cannell 1977). The productivity

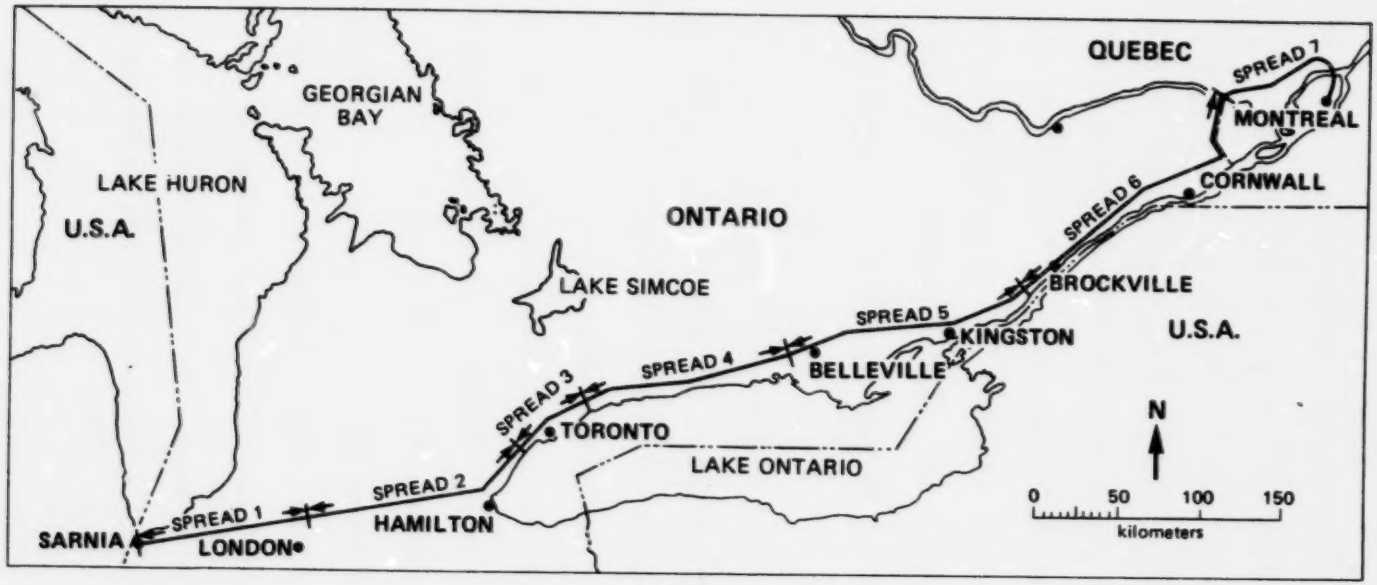

Fig. 1. Sarnia-Montreal oil pipeline right-of-way.

to topsoil relative to the subsoil below has been illustrated by Halstead et al. (1957) and Eck et al. (1975) among others. Direct information on the impact of pipeline construction on Canadian soils is sparse. The possible impact was discussed recently by Shields (1980). DeJong and Button (1973) and Toogood (1974) found little effect of pipeline trenching on cereal yields on two common soil orders (Chernozemic and Solonetzic) in Western Canada. Marsan et al. (1978b) monitored hay, oats and corn yields in 1978 along 25.6 km of a 61 cm diameter gas pipeline constructed in southwestern Quebec during the winters of 1976 and '77. They estimated that, on 37% of the right-of-way crops were inferior or poor compared with adjacent undisturbed land. They also observed superior right-of-way yields along 41% of the easement.

A very generalized indication of the soils and their agricultural capability along the right-of-way is presented in Table 1. Fine-textured, poorly drained clays were common in Spreads 1, 6 and 7. Most of the shallow soils over bedrock occur in Spreads 2 and 5. Stoniness was a hazard in many of the soils of Spreads 5, 6 and 7. The best agricultural soils were in Spreads 1, 2 and 4, although pockets of productive soil occur also in Spreads 6 and 7.

Some of the problems expected along the route were directly related to soil and land features. For example, the potential for soil compaction, subsoil mixing and drainage disruption was greatest in Spreads 1, 6 and 7 because of the poorly drained clays. Rock fragment problems due to rock blasting were important in Spreads 2 and 5 where

Table 1. General Characteristics and Agricultural Capabilities of Soils on Sarnia-Montreal Oil Pipeline Right-of-way

Spread	Length (km)	Counties/Municipalities	Construction Period	General Soil Characteristics*	Soil Capability for Agriculture**
1	122.	Lambton, Middlesex	Sept. - Dec. 1975	About 2/3 of this spread passes through clay-textured soils. Other soil materials are loam till, silt loam, sand and gravel.	Almost exclusively Classes 1 to 3. Poorly drained soils are 2w. Soils on rolling topography in Middlesex and Oxford Counties are mostly 3t.
2	129.	Oxford, Waterloo, Hamilton-Wentworth, Halton, Peel	Sept. - Dec. 1975	Varied assortment of soils. About 10% of this spread passes through shallow soils over bedrock.	Soil capabilities range from Classes 1 and 2 on level clay loam, loam and silt textures to Class 7 on the shallow soils over bedrock.
3	41.	Toronto	Sept. - Dec. 1975	Mostly clay loam and loam textures.	Almost entirely within Metropolitan Toronto, so agricultural capabilities are irrelevant.
4	138.	Durham Northumberland	Sept. - Dec. 1975	High proportion of well and imperfectly drained, medium-textured soils in Durham Region. Further east, there are more sandy soils and rolling topography.	Most Durham Region soils are Class 1 and 2. Those further east, in Northumberland County, range mostly between 2 and 6.
5	144.	Hastings, Lennox and Addington, Frontenac	Oct. 1975 - March 1976	About 1/3 of this spread (30 miles), passes through shallow soils over bedrock. Another 1/3 passes through poorly drained clays.	The shallow soils over bedrock are Classes 6 and 7; the poorly drained clays are 3w. Most other soils range between 1 and 4.
6	145.	Leeds, Grenville, Dundas, Stormont Glengarry	Oct. 1975 - March 1976	High proportion of poorly and imperfectly drained clays along this spread. Lesser amounts of soils on stony and rolling till landforms.	The clays with drainage problems are Classes 2w and 3w. Soils on the upland tills range from 2 to 6 depending on stoniness and topography.
7	111.	Vaudreuil, Argenteuil Deux Montagnes, Terrebonne L'Assomption, Montreal	Oct. 1975 - March 1976	This spread goes through broad areas of imperfectly and poorly drained clays, especially near Mirabel Airport.	The clay soils are mostly Classes 2w and 3w. Other soils on this spread range from 3 to 7.

* Soils information compiled from Ontario and Quebec soil survey reports. Soil reports still in print are available from the Agriculture Ministries of the two provinces.

** Information on soil capability for agriculture was obtained from C.L.I. 1:250,000 maps. These maps are available from: Publishing Centre, Printing and Publishing, Supply and Services Canada, Ottawa, Ont. K1A 0C6

shallow soils occur over bedrock. Stones were a hazard to pipelining wherever they occurred, but especially in Spreads 5, 6 and 7. Surface erosion is a problem in rolling terrain, particulary in Spreads 2, 4 and 5.

Table 2 compares the precipitation over the various Ontario spreads during construction with 30 year normals. Construction in spreads 1, 2 and 4 took place during a somewhat drier than usual period, while in Eastern Ontario construction occurred in wetter than usual conditions. Air temperatures in Ontario were somewhat higher than average in November 1975 and February 1976 (by an average of 3.3°C), but lower than average in December (1.1°C) and January (2.8°C). Warm February weather together with considerable early winter snowfall, prevented deep frost penetration and resulted in several thaw periods. Generally shallow and variable frost penetrations were reported in spreads 6 and 7 by Marsan et al. (1978a). They also observed minimal frost penetration in poorly drained soils in Vaudreuil county, Quebec, in the winter of 1976. Adequate frost penetration (20 cm) was, however recorded in well drained soils.

Field observations were made of the soils and crops at other sites along Sarnia-Montreal pipeline route. Measurements of crop yields and of chemical and physical soil properties of both right-of-way and adjacent areas at selected field sites were also made. In addition three greenhouse experiments were carried out, one to measure yield response of corn to various fertility treatments of selected right-of-way soils, another to evaluate the contribution of topsoil organic nitrogen to yield, and a third to assess the effects of moisture on soil compactability and of relatively small increases in soil bulk density on corn yields.

Table 2. Monthly precipitation totals expressed as percentages of 30 year normals for the six Ontario spreads during construction

Spread	1975			1976		
	Sept.	Oct.	Nov.	Dec.	June	Feb.
	% of Normal*					
1	80	40	85	110	180	115
2	95	50	90	115	145	110
4,5	115	65	80	135	120	105
6	150	105	100	115	115	155

* Data from Monthly Records, Atmospheric Environment Service, Downsview, Ontario

2. MATERIALS AND METHODS

2.1 Field Sites

Sites on and off the right-of-way were selected for monitoring yields in spreads 1, 4 and 6. Yields on the spread 1 sites were estimated in 1976, 1977, 1978 and 1979, yields from the spread 4 site were measured from 1977 through 1979; yields at the spread 6 sites were estimated in 1977. Yields at one of the spread 6 sites were also determined in 1979.

Crops and fertilizer use on the spread 1 sites are summarized in Table 3. Applications of P and K fertilizer on these sites were equal to, or greater than those recommended for Ontario (O.M.A.F. 1979). Nitrogen applications to small grains and to corn were lower than recommended.

2.2 Crops

Crops were sampled just prior to harvesting by the farmers. Yield samples were taken over the trench, on the work (stringing) area, and in the undisturbed, adjacent field. (The trench and work areas will subsequently be referred to as construction zones.) For cereal and forage crops, four randomly selected square meter areas from each zone were harvested. With row crops (corn, soybeans), four randomly selected 2 m row lengths from each zone were harvested.

With exception of the grain corn plots, crops were clipped at about 2.5 cm above the soil surface. Only the cobs were collected from the grain corn plots. Crop heights at both the yield sites and also at other selected sites along the right-of-way were measured on July 20-21, 1976 and August 11-12, 1979. In each zone the heights of 10 randomly selected plants were recorded.

Table 3. Crops and fertilizer use on Perth and Brookston series sites in spread 1.

Site	Year	Crop	Fertilizer Use (kg/ha)		
			N	P_2O_5	K_2O
		Perth			
	1976	Barley	+	+	+
1	1977	Grain corn	143	125	63
	1978	Grain corn	27	108	54
	1976	Soybeans	31	125	63
3,4	1977	Mixed grain	31	125	63
	1978	Winter wheat	91(59)**	125	63
		Brookston			
	1976	Soybeans	22	90	45
1	1977	Soybeans	22	90	45
	1978	Soybeans	22	90	45
	1976	Grain corn	22	90	45
2	1977	Barley	61	38	38
	1978	Soybeans	22	90	45
	1976	Grain corn	31	125	63
3	1977*	Mixed grain	27	108	54
	1978	Grain corn	31	125	54

* right-of-way received 39 tons/ha solid dairy manure and 40 kg/ha of N, 161 kg/ha of P_2O_5, and 81 kg/ha of K_2O after harvest in 1976.

\+ data not available

** amount in brackets was spring applied; remainder was applied at seeding in 1977.

Crop samples were dried at 70°C and harvest moisture content of silage corn samples calculated. Soybeans and cereals were threshed; grain and straw yields were recorded.

Phosphorus and K contents of the crops were measured after ignition of samples at 350°C and digestion in 6N HCl. Determinations of P and K were made using the ammonium molybdate method (with ascorbic acid as reductant) and atomic absorption spectrophotometry respectively. The macro-Kjeldahl method (including NO_2^- + NO_3^-) was used to determine total N content in plant material.

2.3 Soil Physical Properties

At harvest in 1976 and 1977, duplicate aluminum cylindrical cores (7.5 cm x 7.5 cm) of soil were collected from the 0-15 cm and 15-30 cm layers of the construction zones of the spread 1 and spread 4 (only 1977) sites. Sufficient amounts of soil were also collected from each layer of each zone at all sites using a "T" sampler. Surface soil samples were also collected at five other sites in spread 1 and at 15 sites in spread 6 in September 1976. Saturated hydraulic conductivities (K_h) of the cores were measured using a 2.5 cm constant head device (McKeague 1978). Bulk density (Bd) of each core was also determined after drying saturated cores overnight at 105°C. Particle size distributions were determined using the pipette method (McKeague 1978). Triplicate cores from the 0-15 cm layer of each zone of the Brookston series site number 2 were taken in September 1979 prior to harvest. Soil water desorption curves of these 1979 cores were determined according to the method of Topp and Zebchuk (1979).

Cone penetrometer readings were made in June 1978 and May 1979 on the spread 1 sites using a commercially available cone penetrometer. Readings of the maximum pressure required to drive the cone (1.5 cm^2 base, 30^o) to a depth of 15 cm in each zone were recorded. Twenty measurements of cone index (C.I.) were made in each zone of each site in both years. Atterberg limits of the 0-15 cm layer of each zone at selected sites were also determined according to standard methods (McKeague 1978).

2.4 Soil Chemical Properties

Bicarbonate extractable P (0.5 M $NaHCO_3$, pH=8.5), ammonium acetate (NH_4OAc) exchangeable K, total N, organic carbon (wet combustion, titration method), inorganic carbon (approximate gravimetric method), pH (in 1:1 soil:water suspension) and cation exchange capacity (exchangeable by NH_4OAc, pH 7) were determined on soil samples collected from the sites. Details of the particular methods can be found in McKeague (1978).

2.5 Greenhouse Studies

Three greenhouse experiments were conducted. The objective of the first was to compare response to N, P and K fertilizer of corn grown on fall (unfrozen, wet conditions) and on winter (frozen) constructed right-of-way soils. Two soils, a lacustrine clay loam (North Gower series) and a heavy textured till (Morrisburg series) from spread 6 were selected for comparison. The fall construction sites had been topsoil-stripped over the trench prior to construction. After pipeline installation, subsoil was replaced first, followed by topsoil. A berm was left over the pipeline to allow for subsequent subsidence of the backfill. Clean up (chisel plowing and stone picking) was carried out as convenient; however, soils were often worked while wet.

Samples from two winter constructed sites (1976) were taken from a nearby natural gas pipeline right-of-way. These soils were frozen at both sites during construction (A.F. MacKenzie, personal communication). Topsoil was not stripped and clean-up was delayed until soils conditions were suitable for working.

Soil was collected from the 0-15 cm layer of each construction zone at all sites. Sampling sites were close to those sites selected for study by Mackenzie (1977, 1978a, b). Soils were air-dried and sieved through a 1.25 cm screen. About 5.5 kg of soil were packed in plastic pots to a Bd of 1.2 g/cm^3. Treatments included a control (no fertilizer added), N, P, K, NP, NK, PK, NPK, and 2X NPK, where N, P and K denote application rates of 168, 99 and 186 kg/ha of N, P and K respectively. Fertilizer used were NH_4NO_3, $CaH_4(PO_4)_2.H_2O$ and KCl. Each treatment was replicated four times. Three corn plants

(Zea mays L. Co-op H-7) were grown in each pot for 10 weeks at which time all three whole plants were harvested, dried at 70°C and then weighed. Subsamples were ground and analysed using methods described above. Soils were also sampled and analysed for pH, C.E.C. total N, soil test P and K and particle size distributions using methods outlined above.

The objective of the second greenhouse experiment was to evaluate the effects of mixing topsoil (0-15 cm layer) with subsoil (20-40 cm layer) on corn yields and uptake of N under moderate N fertilization (112 kg/ha of N). Three soils of differing texture which occur commonly in Eastern Ontario, Grenville loam, Castor silt loam and Rideau clay were used in this experiment. Soil mixtures were 100% topsoil, 75% topsoil (25% subsoil), 50% topsoil, 25% topsoil and 0% topsoil (100% subsoil). Six kg of soil were packed in pots to a Bd of 1.1 g/cm^3; all pots received fertilizer at 112 kg/ha of N, P and K prior to seeding corn. Each treatment was replicated four times. Three corn plants were grown in each pot for 10 weeks. Yields (D.M.) and N contents of corn were measured.

The objectives of the third greenhouse experiment were to study the effects of compacting either subsoil or topsoil of varying moisture contents on vegetative corn yields. Standard Proctor compaction curves (Lambe 1951) for the surface and subsurface layers of the three soils used in the topsoil-subsoil experiment were determined. For the compacted subsoil treatments, about 3 kg of sieved subsoil of varying moisture content were packed in plastic pots to an initial Bd of 1.1 g/cm^3.

Selected moisture contents were 25%, 50%, 100% and 125% of optimum moisture contents for compaction (Proctor) of the subsoils. Compaction was accomplished by applying a pressure of 4.0 kg/cm^2 to a steel plate which completely covered the surface of the subsoil in the pot. The compaction treatment was applied five times to each pot. Roughly 3 kg of topsoil were then added to each pot and packed to Bd of 1.1 g/cm^3.

For the compacted topsoil treatments, 3 kg of subsoil of the same moisture content as was used in the subsoil treatments were packed in the pots to a Bd of 1.1 g/cm^3. Topsoil of varying moisture content (25, 50, 100 and 125% of the optimum moisture content for compaction of each topsoil) was added to each pot and packed to a Bd of 1.1 g/cm^3. Topsoil was then compacted in the same way at the same pressure as in the compacted subsoil treatments described above. Slightly varying amounts of top and subsoil were required for each treatment so that depth of each layer of each soil was kept constant at 7.5 cm. Total soil depth of each pot was 15 cm. The same N-P-K fertilizer rate (112 kg/ha) as used in the second experiment was applied except that an additional 112 kg/ha of N was applied between three and four weeks after emergence. Three corn plants were grown in each pot for 10 weeks. Dry matter corn yields were measured.

The compacting pressure used in this experiment (4.0 kg/cm^2) was selected to approximate the rear tire contact pressure exerted on soils by trucks fully loaded with the steel pipe used in the Sarnia-Montreal extension. This contact pressure is considerably greater than pressures normally applied to soils by farm machinery tires. Raghavan et al. (1976) measured the contact pressures of several tractors with varying

numbers and sizes of tires. Contact pressures ranged from about 0.2 kg/cm^2 for a small unloaded tractor to about 1.1 kg/cm^2 for a four-wheel drive tractor weighing 6300 kg pulling a load of almost 3,500 kg.

3. RESULTS AND DISCUSSION

3.1 Effects of Pipeline Installation

3.1.1 Crop Yields

Crop yields at most sites were highly variable on the right-of-way, especially in 1978 and 1979. Since only four replicates were taken, mean right-of-way yield reductions of less than 20% were not usually statistically significant at $p < 0.05$. More replicates at each site would probably have resulted in more sites with significant yield differences between on and off right-of-way sites. Also, it should be noted that the Tukey W procedure, which was applied to these data, is known to be a conservative test of significance (Steel and Torrie 1960); the more common least-significant-difference (l.s.d.) criterion is only 80% of Tukey's W value at $p < 0.05$.

Grain dry matter yields at the three Brookston sites were substantially reduced on the right-of-way in both 1976 and 1977 (Table 4). Yields on the trench and on the work area averaged 45% and 39% of adjacent field yields respectively. In 1978, right-of-way yields were higher than those on adjacent undisturbed land at one corn and one soybean site, but this trend was reversed in 1979. At the site with substantial yield reduction in each of the four years, yields over the trench improved from 28% of those of the undisturbed area in 1976 to 77% in 1979, while on the work area yields were 22% and 54% of those on undisturbed land in 1976 and 1979 respectively. Although cropping practices changed on all sites, yield differences (expressed as percentages of the undisturbed field) decreased over the first four years after pipeline installation on Brookston clay loam.

Table 4. Dry matter grain yields of crops grown on Brookston and Perth soils on and off pipeline right-of-way (Spread 1 - Lambton County)

Site	Year	Crop	Grain Yield (t/ha) Trench	Work Area	Undist. Field	Tukey's w-statistic ($p < .05$)	Straw Yield (t/ha) Trench	Work Area	Undist. Field	Tukey's w-statistic ($p < 0.05$)
			Brookston Series							
1	1976	Soybeans	1.30	0.98	1.68	0.71*	-	-	-	-
	1977	Soybeans	1.29	1.39	1.99	0.49	-	-	-	-
	1978	Soybeans	1.85	1.44	1.58	1.24	-	-	-	-
	1979	Winter wheat	2.47	2.32	2.58	0.68	6.21	5.51	8.06	2.45
2	1976	Corn	1.56	1.23	5.61	1.50	-	-	-	-
	1977	Barley	1.25	1.46	4.18	1.06	1.20	1.49	3.87	0.61
	1978	Soybeans	1.36	1.10	2.15	0.50	-	-	-	-
	1979	Soybeans	2.31	1.64	3.01	0.41	-	-	-	-
3	1976	Corn	1.24	0.62	3.11	1.49	-	-	-	-
	1977	Mixed grain	0.89	0.84	2.92	1.05	1.40	1.33	3.48	0.91
	1978	Corn	8.14	6.20	5.22	3.54	-	-	-	-
	1979	Corn	6.14	5.40	6.99	2.61	-	-	-	-
			Perth Series							
1	1976	Barley	N.D.[t]	N.D.	N.D.	N.D.	-	-	-	-
	1977	Corn	4.12	3.35	6.47	0.67	-	-	-	-
	1978	-	N.D.	N.D.	N.D.	-	-	-	-	-
	1979	Winter wheat	2.32	2.10	2.46	0.58	4.91	4.66	5.73	1.50
2	1976	Soybeans	1.38	1.80	2.19	1.19	-	-	-	-
	1977	Soybeans	2.09	2.11	2.85	0.24	-	-	-	-
	1978	Soybeans	2.62	1.06	1.88	1.52	-	-	-	-
	1979	Soybeans	1.23	0.88	1.13	0.41	-	-	-	-
3	1976	Soybeans	3.45	2.15	3.92	1.00	-	-	-	-
	1977	Mixed grain	1.68	2.97	4.28	1.84	1.85	3.11	4.88	2.06
	1978	Winter wheat	3.56	3.45	3.86	1.08	4.93	5.10	6.37	1.09
	1979	Alfalfa**	1.16	1.04	1.08	0.32	-	-	-	-
4	1976	Soybeans	1.76	1.62	3.05	1.42	-	-	-	-
	1977	Mixed grain	2.78	2.67	4.04	1.25	3.06	3.04	4.17	1.51
	1978	Winter wheat	3.67	3.29	4.22	1.47	5.37	4.89	6.73	2.41
	1979	Alfalfa**	N.D.	N.D.	N.D.	-	-	-	-	-

t not determined

**3rd cut

* means within each row which differ by more than Tukey's w value are significantly different at 5% probability level. l.s.d.s. can be determined by multiplying Tukey's w value by 0.63 ($p < .10$), by 0.80 ($p < .05$), and by 1.20 ($p < .01$).

Similar results were obtained on the somewhat better drained Perth plots. The substantially lower yields observed in the first two years (35% and 34% on the trench and work area respectively) improved dramatically in the third and fourth years, but still had not reached those of the undisturbed fields by 1979. In general, cereal straw yields from both the Brookston and Perth sites reflected those for grain (Table 4).

In contrast to the results on the generally heavy textured soils of spread 1, grain corn reductions on Brighton sand (spread 4) did not occur until 1979 (Table 5). Visual observations suggested that nitrogen deficiency was responsible for the lower yield on the right-of-way in 1979.

Silage corn yields were depressed on the right-of-way in 1977 at all four loamy sites in spread 6 (Table 5). Reductions averaged 42% and 45% on the trench and work area respectively. Data from one of these sites in 1979 indicated a relative improvement with time, although a substantial yield reduction was still apparent in 1979.

Ramsay and MacKenzie (1978) measured yields on and off the Sarnia-Montreal pipeline right-of-way at 91 sites located in all seven spreads in 1977. Over all sites, they found a statistically significant reduction in yield of about 34%. Work area reductions at the twelve sites in this report in 1977 were in fairly good agreement with Ramsey and MacKenzie's results and averaged 43%. Only two sites, one in grain corn on sand and one in mixed grain on clay loam, had non-significantly different yields on and off the right-of-way in this year. Ramsay and MacKenzie observed non-significantly lower right-of-way yields on sites seeded to soybeans and grain corn, but they did find significantly lower

Table 5. Dry matter corn yields grown on soils of varying textures on and off pipeline right-of-way (Spread 6 - Leeds, Dundas and Glengarry counties, and Spread 4 - Regional Municipality of Durham)

Soil Series	Year	Crop	Yield (t/ha)			Tukey's w-statistic ($p < .05$)
			Trench	Work area	Undist. field	
---------- Spread 6 ----------						
Matilda loam	1977	silage Corn	3.34	4.70	7.60	3.00 *
Matilda loam	1977	Silage corn	10.73	8.71	15.04	4.10
Osgoode loam	1977	Silage corn	10.00	9.97	15.56	3.49
Morrisburg clay loam	1977	Silage corn	8.29	5.99	16.43	3.92
	1979		9.78	6.55	14.48	1.85
Belmeade (North Gower) clay loam	1978	Grain corn	5.90	6.59	7.32	3.70
---------- Spread 4 ----------						
Brighton sand	1976	Grain corn	3.63	3.65	4.32	1.43
	1977	Grain corn	4.43	3.39	5.00	2.39
	1978	Grain corn	4.39	3.35	4.96	2.37
	1979	Grain corn	3.63	2.83	5.05	1.40

* means within each row which differ by more than Turkey's W value are significantly different at the 5% probability level.

right-of-way yields on spring grains (yield reduction of 45%), hay (reduction of 43%), winter wheat (reduction of 37%) and silage corn (reduction of 20%) sites. They also noted that yield reductions due to pipelining increased with increasing soil clay contents. The limited 1977 data presented in Table 4 and 5 tend to confirm this finding. The somewhat inconsistent results obtained in these two studies with respect to the sensitivity of soybeans and corn probably demonstrate the importance of site factors on the effects of pipeline construction on crop yields.

3.1.2 Crop Heights

Crop height measurements on and off the Sarnia-Montreal pipeline right-of-way were made at selected sites in spreads 1, 2 and 4 in late July 1976, and in spreads 1, 2, 4, 5 and 6 in early August 1979. For the sites where midseason crop heights and final yields are available, a faily good 1:1 relationship existed between right-of-way heights and final grain corn and soybean dry matter yields (Fig. 2). No data were available for cereals. At clay and clay loam sites, right-of-way crop heights increased from about 60% of undisturbed in 1976 to about 80% in 1979 (Table 6); at silt loam sites, heights increased from about 42% in 1976 to about 76% in 1979. At loam sites the improvement was about 20% (Table 7). Crop heights on the right-of-way where it crossed sandy loams and sands averaged about 75% of undisturbed in 1979. Despite considerable variability in the soil texture at the 1979 sites, crop height reductions due to pipeline installation were similar across all sites.

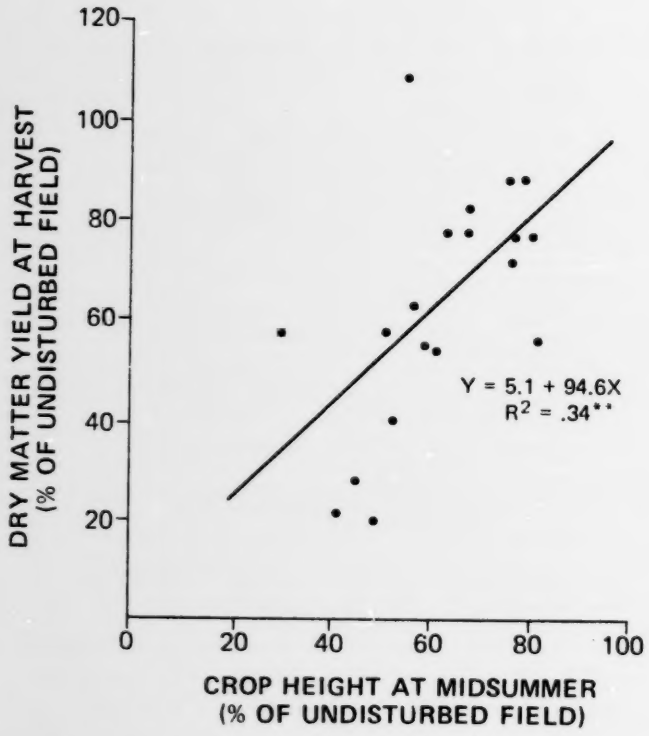

Fig. 2. Relation between dry matter yields at harvest and midsummer crop heights of grain corn and soybeans grown on the Sarnia-Montreal pipeline right-of-way.

Table 6. Right-of-way crop heights on clays and clay loams, and silt loam soils expressed as percentages of those from adjacent undisturbed sites.

Soil series	Spread no.	Height					
		1976			1979		
		Crop	Trench % of undisturbed	Work % of undisturbed	Crop	Trench % of undisturbed	Work % of undisturbed
		Clays and Clay Loams					
Brookston	1	Soybeans	77	51	Soybeans	63	61
	1	Corn	52	49	corn	79	80
	1	Corn	45	41	Wheat	-	-
Perth	1	Soybeans	57	68	Soybeans	56	67
	1	Barley	114	68	-	-	-
	1	Barley	70	69	Corn	74	86
	1	-	-	-	Corn	74	80
	1	Soybeans	76	59	Alfalfa	-	-
	1	Soybeans	30	0	Alfalfa	-	-
Huron	1	Mixed grain	63	86	Corn	90	90
	1	Barley	72	93	Corn	-	-
	1	Barley	63	59	-	-	-
	2	Corn	22	29	Mixed grain	99	84
Lansdown	5	-	-	-	Mixed grain	67	71
Napanee	5	-	-	-	Oats	85	90
Morrisburg	6	-	-	-	Corn	88	91
Means			62	56		78	80
		Silt Loams					
Huron	1	Corn	41	43	Corn	74	98
Tuscola	1	Corn	43	49	Corn	81	84
					Beans	92	86
Embro	1	Corn	40	37	Mixed grain	45	53
Means			41	43		73	80

Table 7. Right-of-way crop heights loams, sandy loams, and sand soils expressed as percentages of those from adjacent undisturbed sites.

Soil series	Spread no.	Height					
		1976			1979		
		Crop	Trench % of undisturbed	Work % of undisturbed	Crop	Trench % of undisturbed	Work % of undisturbed
		Loams					
Brisbane	1	Barley	80	79	Soybeans	97	91
London	1	Corn	32	39	Corn	63	87
		Corn	-	-	Oats	76	78
London	1	Corn	39	36	Corn	49	72
		Corn	-	-	Oats	41	59
Guelph	2	Corn	67	63	Corn	70	81
		-	-	-	Oats	82	85
Bondhead	4	Oats	58	67	Corn	76	88
	4	Corn	-	-	Beans	68	60
	4	-	-	-	Oats	63	81
	4	Corn	-	-	Corn	83	92
Percy	4	-	-	-	Corn	77	90
Otonabee	5	-	-	-	Corn	58	81
Matilda	6	Corn	-	-	Corn	84	97
Osgoode	6	Corn	-	-	Oats	57	73
	6	Pasture	-	-	Mixed grain	71	75
Means			55	57		70	81
		Sandy Loams and Sands					
Grimsby	2	Potatoes	-	-	Potatoes	64	82
Guelph	2	Barley	-	-	Barley	64	75
		-	-	-	Oats	74	83
Bondhead	5	-	-	-	Corn	58	81
Grenville	6	-	-	-	Corn	76	81
Uplands	6	Corn	-	-	Corn	70	91
Brighton	4	Corn	-	-	Corn	76	81
Means						69	82

Analysis of crop heights pooled over all soils demonstrated the improved right-of-way heights of corn and beans (soybeans and beans) in 1979 compared with 1976 (Table 8). Soybean heights improved by 15% and 30% over the trench and work area respectively between 1976 and 1979. Corn heights improved even more dramatically. In contrast there appeared to be little change in the heights of cereals between 1976 and 1979.

3.1.3 Nutrient Content of Crops

Nitrogen, P and K concentrations in spring sown mixed grain grown on the right-of-way were higher than those in grain grown on undisturbed land in 1977 (Table 9). Similar findings were obtained by Ramsay and MacKenzie (1978). However, barley nutrient concentrations were not affected by construction zone. In contrast, both the N and P concentrations in soybeans grown on undisturbed land were higher than those of soybeans grown on the trench. Contents of N in soybeans grown on the work area were intermediate. The N concentrations of both silage and grain corn were not significantly affected by construction zones. Corn grown on undisturbed land tended to have somewhat lower K concentrations suggesting that the maturity of right-of-way corn was retarded; this was confirmed by moisture concentrations of silage corn at harvest. Silage corn moisture contents at harvest at the 1979 Morrisburg sites were 64 (±1)%, 78 (±3)% and 76 (±3)% for the undisturbed field, trench and work area respectively.

Table 8. Right-of-way crop heights expressed as percentages of those from adjacent undisturbed fields.

Crop	1976			1979		
	No. of sites	Trench	Work area	No. of sites	Trench	Work area
		Height %				
Soybeans & beans	4	60	45	5	75	73
Corn	9	42	43	19	74	86
Cereals	7	74	74	12	69	76

Table 9. Nitrogen, phosphorous and potassium contents of small grains, silage corn, grain corn and soybeans grown on and off pipeline right-of-way in 1977 .

Crop	No. of sites	N content (%)			P content (%)			K content (%)		
		Trench	Work area	Undist field	Trench	Work area	Undist field	Trench	Work area	Undis field
Mixed grain	3 *	2.19	2.18	1.89	0.43	0.43	0.39	0.49	0.52	0.47
Tukey's w statistic			(0.18)			(0.02)			(0.04)	
Barley	1	1.98	2.12	1.89	0.41	0.46	0.45	0.46	0.52	0.57
Tukey's w statistic			(0.29)			(0.13)			(0.12)	
Silage corn	4	0.98	1.06	1.07	0.20	0.21	0.20	0.78	0.82	0.77
Tukey's w statistic			(0.19)			(0.03)			(0.13)	
Grain corn	2	1.66	1.73	1.77	0.34	0.38	0.33	0.32	0.34	0.30
Tukey's w statistic			(0.19)			(0.06)			(0.04)	
Soybeans	2	5.96	6.07	6.19	0.46	0.46	0.50	1.63	1.61	1.60
Tukey's w statistic			(0.18)			(0.03)			(0.11)	

* Means which differ by a value greater than Tukey's w statistic are significantly different at $p<0.05$.

3.1.4 Soil Chemical Properties

Work area surface soils in September 1976 had significantly lower cation exchange capacities (C.E.C.) and total N concentrations, but higher pH values than soils on adjacent undisturbed land (Table 10). Exchangeable K contents were significantly lower on the right-of-way at some of the spread 6 sites (Eamer loams and Allendale sandy loam), but were not affected on other soil series in either spread 1 or 6. With exception of the clay loam textured spread 6 sites (North Gower series) extractable P levels tended to be lower on the right-of-way than off. Substantially lower right-of-way P and K soil tests were observed in fields known to have received fairly heavy annual applications of manure prior to pipeline construction. In general, P and K fertility levels both on and off the right-of-way were moderate in September 1976 (O.M.A.F. 1979).

Cation exchange capacities of soils depend primarily on organic matter and clay contents. Clay contents in the 0-15 cm layer on and off the right-of-way were measured on the six 1976 yield sites (Perth and Brookston series). Differences between right-of-way and undisturbed soil C.E.C.'s were strongly related to differences in total N and clay contents:

$$\Delta CEC = -2.8 + 87.7 \times \Delta \text{total N} + 0.34 \times \Delta \text{clay} \qquad R^2 = 0.95^{**}$$

where ΔCEC = CEC (right-of-way) - CEC (undisturbed field) (me./100g)

Δtotal N = total N (right-of-way) - Total N (undisturbed field) (%)

ΔClay = Clay (right-of-way) - Clay (undisturbed field) (%)

Measurements of inorganic N in both undisturbed and right-of-way soils showed values uniformily below 0.002%. Thus, the observed lower total N

Table 10. Some soil chemical properties of the 0-15 cm layer of the work (stringing) areas of the Sarnia-Montreal oil pipeline right-of-way and adjacent undisturbed fields in the fall of 1976.

Soil series	No. of sites	Cation Exchange capacity (me/100g)		Total Nitrogen (%)		Extractable Phosphorous ppm		Exchangeable Potassium ppm		pH	
		Undist. field	Work area	Undist. field	Work area	Undist. field	Work area	Undist. field	Work area	Undist. field	Work area
		Spread 1									
Brookston	4	25.9	18.9	0.20	0.15	21	17	137	129	7.5	7.8
Perth	7	20.1	14.8	0.21	0.16	25	17	129	113	7.3	7.8
		Spread 6									
North Gower	5	37.3	24.6	0.41	0.24	17	31	188	176	6.6	7.5
Eamer	3	27.1	22.3	0.23	0.17	27	11	196	113	7.2	7.6
Grenville	6	21.3	18.2	0.29	0.20	18	14	90	86	6.8	7.6
Allendale	1	26.9	17.3	0.32	0.12	7	6	149	102	7.2	7.6
Mean		25.2	19.2	0.26	0.17	21.0	18.9	141	121	7.1	7.7
l.s.d.	.05	4.8		0.05		6.4		31.3		0.2	
	.01	6.4		0.07		8.6		43.0		0.3	

concentrations on the right-of-way reflect dilution of the organic matter rich surface (A horizon) with subsurface soils which contain lower amounts of organic matter. Acton et al. (1979) analysed some intensively cropped Perth and Brookston soils in southern Huron and Essex counties. These soils are similar although Perth is slightly better drained.

Organic C contents and depth of the surface Ap horizon of cropped Brookston soil in Essex County averaged about 1.9% and 25 cm respectively; the horizon below the Ap (Bg) ranged in depth from about 25 to 50 cm and had an average organic C content of about 0.4%. The parent material, of the Brookston series in Essex consists of calcareous clay, usually within about 100 cm of the surface, and has organic C contents of 0.3-0.6%. Perth and Brookston soils in Huron county are similar but tend to have somewhat higher organic C contents in the surface Ap horizon. Organic C of the surface (0-15 cm) layers of the 1977 spread 1 (Lambton County) yield plots were consistently lower in the right-of-way than in the adjacent undisturbed field (Table 11). Organic C levels in the undisturbed spread 1 sites (Brookston and Perth soils) were consistent with those obtained by Acton et al. (1979). Assuming Perth and Brookston subsoil has average organic carbon content of 0.5%, the organic C data indicate right-of-way topsoil dilutions of 20-50% in the surface 0-15 cm layer of yield sites in spread 1.

In the 15-30 cm layer, significantly lower organic C concentrations were observed in the undisturbed field than on the work area (Table 11). Over the trench, however, organic C in the 15-30 cm layer tended to be lower than in the undisturbed field. Inorganic C contents in the work area were intermediate between those observed over the trench and

Table 11. Inorganic and organic carbon contents (in per cent) of the 0-15 cm and 15-30 cm layers of Sarnia-Montreal oil pipeline right-of-way and of adjacent undisturbed fields (sampled Sept. 1977).

Soil series	Spread	No. of sites	Depth	Inorganic C			Organic C		
				Trench	Work area	Undist. field	Trench	Work area	Undist. field
Brookston	1	3	0-15	2.1	1.5	0.1	1.1	1.5	1.7
			15-30	2.4	1.2	0.2	1.0	1.4	1.7
Perth	1	4	0-15	1.9	1.0	0.3	1.7	1.6	2.1
			15-30	3.2	0.4	0.2	0.6	1.3	1.1
Brighton	4	1	0-15	0.7	0.5	0.2	0.6	0.7	1.0
			15-30	1.4	1.9	0.3	0.4	0.2	0.3
Matilda	6	2	0-15	1.8	1.2	0.5	1.3	1.9	2.4
			15-30	2.2	0.8	0.3	0.4	1.5	0.8
Osgoode	6	1	0-15	1.3	0.7	0.0	0.7	1.6	1.7
			15-30	0.6	0.5	0.2	1.5	2.1	0.5
Morrisburg	6	1	0-15	1.2	1.5	0.4	2.0	1.4	2.7
			15-30	1.5	0.7	0.5	0.9	2.8	2.5
Mean			0-15	1.7	1.1	0.3	1.4	1.5	2.0
standard error ($S\bar{x}$)				---(0.1)--------			----(0.1)-------		
Mean			15-30	2.3	0.8	0.3	0.8	1.4	1.2
standard error ($S\bar{x}$)				---(0.1)--------			----(0.05)------		

those in the undisturbed field both in the 0-15 cm and in the 15-30 cm layers (Table 11).

Since both inorganic and organic C contents in the work area zone were affected by construction, it would appear that considerable amounts of subsoil from the trench were spread across the right-of-way, especially in spread 6. Disturbance of the work area by tire rutting alone would probably have had minimal effect on soil inorganic C contents. The increased alkalinity on the right-of-way caused by carbonates from the subsoil was probably not sufficient to create micronutrient or phosphate deficiencies (Russell 1973).

Soil test levels of P and K at the 1977 sites were not significantly affected by pipeline construction (Table 12). The high soil test P value in the undisturbed zone of the Morrisburg site was due to high manure applications prior to construction. The total N data at the 1977 yield sites (Table 12) mirrored the organic C data; thus both parameters indicate relative changes in organic matter levels caused by disturbance.

3.1.5 Physical and Mechanical Properties

Construction zone effects on bulk density (Bd), saturated hydraulic conductibity ($\log K_h$) and cone penetrometer (C.I.) were highly significant ($p < 0.01$) at all spread 1 sites (Table 13). Between-site effects were substantially greater at the Perth than at the Brookston sites. Surface textures of the undisturbed Perth sites varied from sandy clay loam to silt loam; all Brookston sites were clay loam. This greater texture variability of the Perth sites was probably responsible for the significant between-site effects.

Table 12. Bicarbonate ($NaHCO_3$ pH - 8.5) extractable phosphorus and NH_4OAc (pH-7) exchangeable potassium of surface soils (0-15 cm) and total N contents in the 0-15 cm and 15-30 cm layers on and adjacent to Sarnia-Montreal oil pipeline right-of-way in 1977.

Soil series	Extractable P (ug-P/g-soil)			Exchangeable K ppm			Total Nitrogen (%)					
							0-15 cm			15-30 cm		
	Trench	Work area	Undist. field	Trench	Work area	Undist. field	Trench	Work area	Undist. field	Trench	Work area	Undist. field
Brookston	12	10	12	141	137	141	0.12	0.14	0.21	0.10	0.13	0.17
Perth	18	22	20	129	137	137	0.11	0.15	0.19	0.06	0.11	0.09
Brighton	19	24	24	20	31	24	0.05	0.07	0.09	0.02	0.02	0.04
Matilda	9	9	8	47	55	55	0.13	0.19	0.22	0.04	0.15	0.07
Osgoode	15	24	24	141	110	47	0.08	0.15	0.14	0.15	0.22	0.05
Morrisburg	22	27	63	117	98	98	0.20	0.17	0.30	0.12	0.28	0.28
Means	15	18	20	110	110	102	0.12	0.15	0.20	0.08	0.14	0.12
$S\bar{x}$	------(3.0)-----			------(12.0)------			------(0.006)-----			------(0.006)-----		

Table 13. F values from analysis of variance tables for bulk density, transformed (log) saturated hydraulic conductivities of the 0-15 cm and 15-30 cm layers and for cone index values of the 0-15 cm layer of the Brookston and Perth sites.

Parameter	Effect				Reduction in Total Sums of Squares (%)
	Site	Construction zone	SitexZone Interaction	Soil Depth	
	Perth Sites				
Bulk density	25.97**	68.07**	8.04**	1.0	79
$\log_e (K_h)$	185.65**	210.33**	11.66**	1.0	93
Cone index	149.58**	55.94**	3.75	-	59
	Brookston Sites				
Bulk density	2.10	75.33**	1.49	11.72**	75
$\log_e (K_h)$	33.47**	441.15**	1.44	14.18**	89
Cone index	4.46	79.50**	1.68	-	55

**significant at $p < 0.01$

Bulk densities at all Spread 1 sites decreased in the order work area > trench > undisturbed field while K_h decreased in the opposite way, undisturbed field > trench > work area (Table 14). Overall, Bd of work areas were generally less than 10% greater than those in adjacent undisturbed fields; K_h decreased by an average of 38% in the work area compared with the controls. Bulk densities and log K_h were well correlated ($r = -.77^{**}$) for the Brookston sites; void ratios, defined as the ratio of the volume of voids to the volume of solids, were also well related to log K_h (Fig. 3). No relation existed between these parameters at the Perth sites due to between-field variability. Changes in water movement properties as a result of pipeline construction may be more important than the increases in Bd which, on the right-of-way, were not great enough to have had an effect on crop growth (Russell 1973).

Soil water desorption curves of the surface layers of the zones at site 2, Brookston series (Fig. 4) indicated that total porosities, but not drainable porosities (Fig. 5) were reduced by pipeline construction. Drainable porosity is defined as the volume of water drained from a unit volume of saturated soil when the soil moisture pressure is decreased from atmospheric to a given specific negative pressure. Topp (1978) found that Brookston clay topsoil had higher total porosity, but about the same volumetric water content at the permanent wilting point (PWP, water content at a pressure head of 15,000 cm of water) as subsoil (Fig. 6). This was also true of the Brookston soils in this study. Within a given soil texture class, variability in PWP is usually quite small (Salter and Williams 1965). Particle size distributions of the soils at site 2 were

Table 14. Mean bulk density, $\log_e$ saturated hydraulic conductivity, cone penetrometer index and clay content in each zone of the spread 1 sites.

Perth Series					Brookston Series				
		Zone					Zone		
Site	Depth (cm)	Undist. field	Trench	Work area	Site	Depth (cm)	Undist. field	Trench	Work area
				Bulk Density (g/cm^3)					
2	0-15	1.22	1.28	1.28	1	0-15	1.08	1.17	1.20
	15-30	1.25	1.26	1.25	1	15-30	1.11	1.19	1.23
3	0-15	1.10	1.20	1.26	2	0-15	1.10	1.17	1.22
	15-30	1.14	1.22	1.27		15-30	1.10	1.19	1.24
4	0-15	1.13	1.22	1.28	3	0-15	1.08	1.11	1.20
	15-30	1.15	1.23	1.25		15-30	1.12	1.17	1.23
		$S\bar{x}$ - 0.016					$S\bar{x}$ - 0.017		
				$\log_e$ Hydraulic Conductivity (cm/day)					
2	0-15	3.88	3.74	3.66	1	0-15	3.55	3.37	3.03
	15-30	3.92	3.75	3.58		15-30	3.55	3.38	2.93
3	0-15	3.65	3.44	3.00	2	0-15	3.56	3.33	3.07
	15-30	3.61	3.55	3.11		15-30	3.47	3.34	2.95
4	0-15	3.59	3.45	3.17	3	0-15	3.69	3.66	3.31
	15-30	3.55	3.46	3.00		15-30	3.62	3.52	3.08
		$S\bar{x}$ - 0.039					$S\bar{x}$ - 0.045		
				Cone Index (kg/cm^2)					
1	0-15	12.74	20.69	17.05	1	0-15	10.86	17.14	14.46
2	0-15	7.87	12.69	11.64	2	0-15	8.05	15.24	14.82
					3	0-15	9.26	15.11	14.13
		$S\bar{x}$ - 0.61					$S\bar{x}$ - 0.66		
				Clay Content (%)					
2	0-15	9.4	26.4	20.2	1	0-15	34.4	35.6	35.6
	15-30	7.8	27.8	15.6		15-30	39.0	37.6	38.4
3	0-15	32.6	34.4	32.8	2	0-15	30.6	37.8	38.0
	15-30	33.8	36.2	33.4		15-30	34.2	38.6	36.8
4	0-15	22.8	35.6	29.8	3	0-15	17.8	30.0	23.0
	15-30	26.0	37.2	30.2		15-30	19.0	32.6	29.8

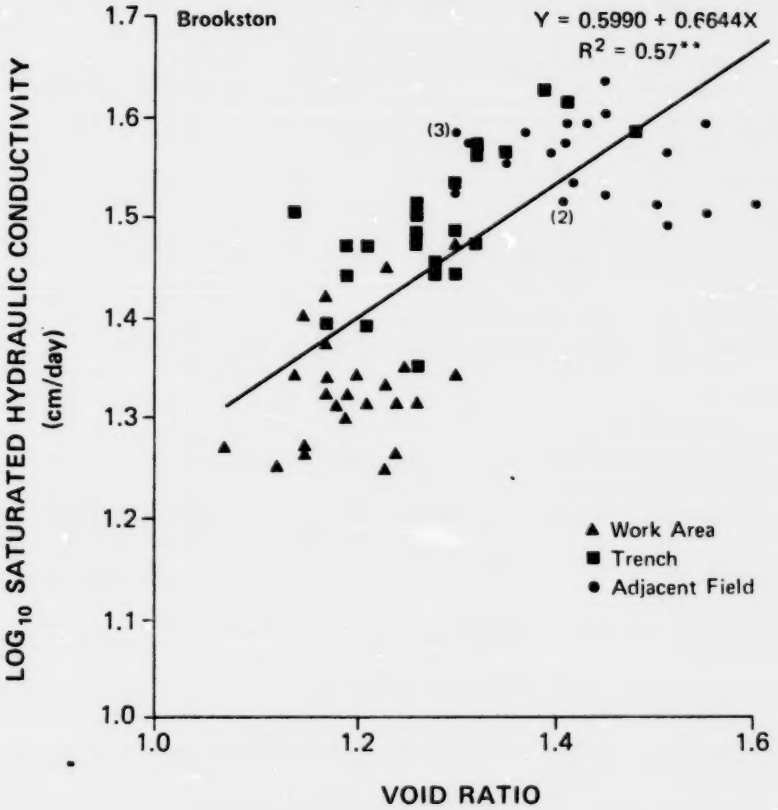

Fig. 3. Relation between $\log_{10}$ saturated hydraulic conductivity and void ratio for the Brookston sites.

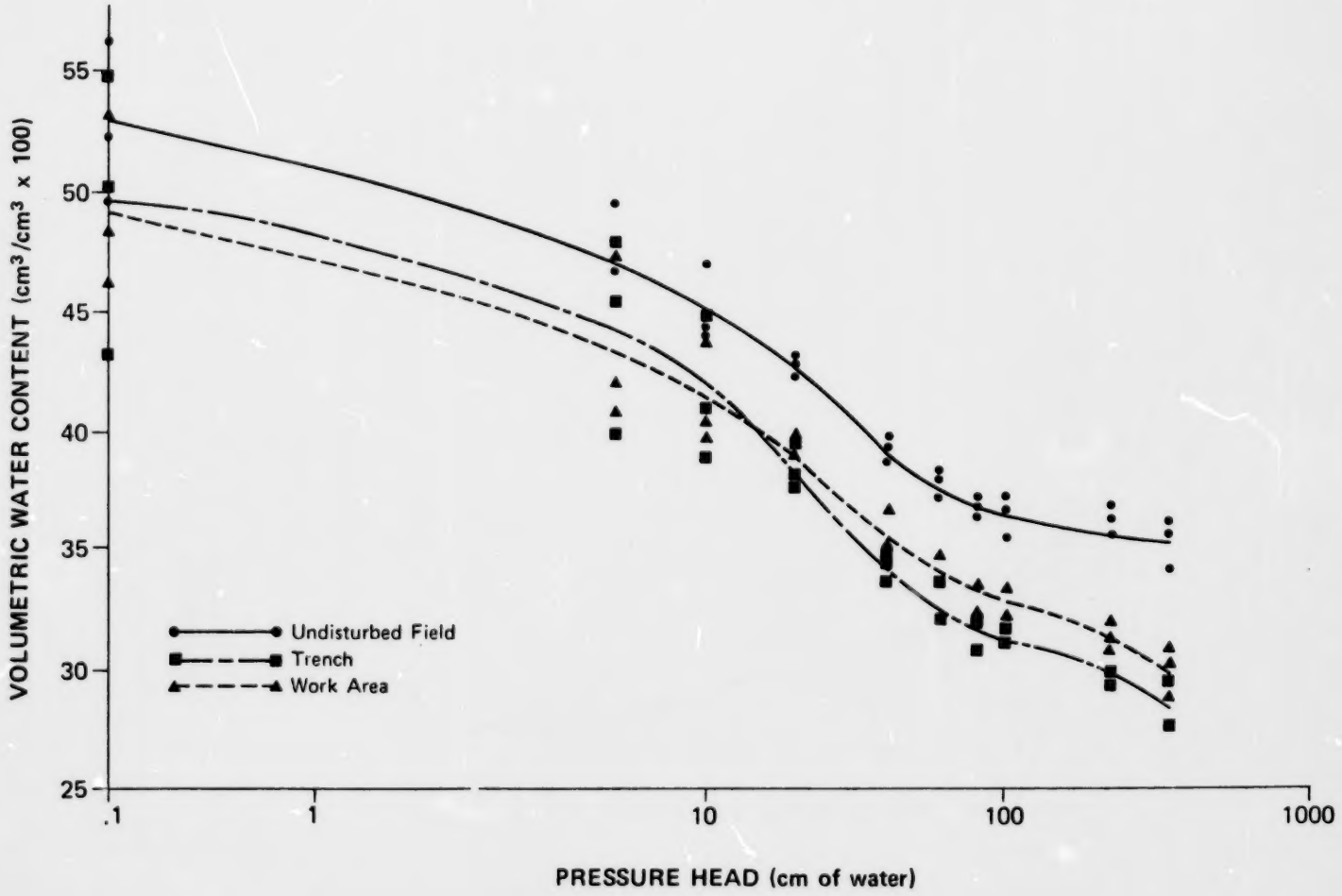

Fig. 4. Water desorption curves of surface soils on and off right-of-way at site 2, Brookston series.

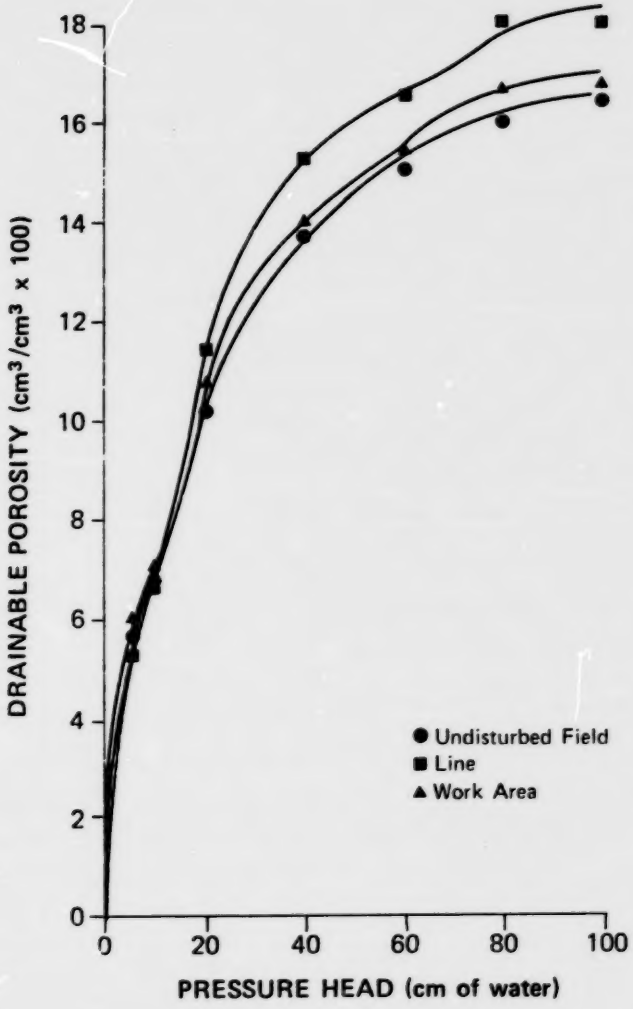

Fig. 5. Drainable porosity - pressure head relations for surface, site 2 Brookston series soils.

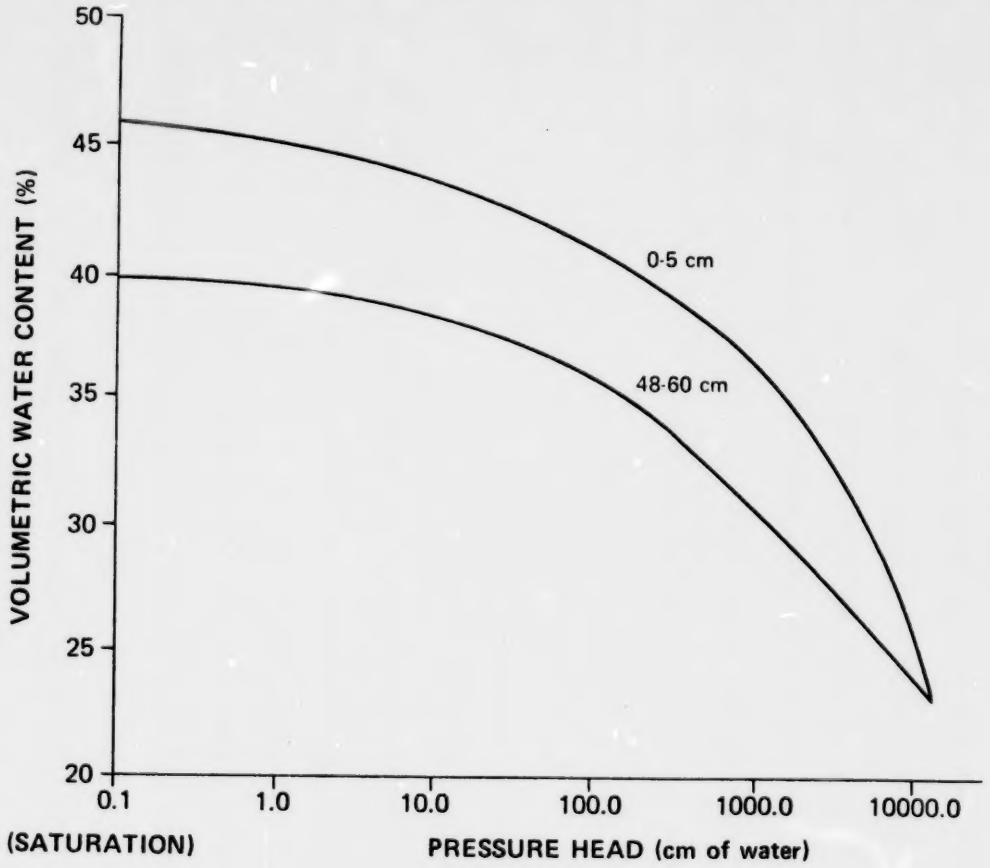

Fig. 6. Water desorption curves for surface and subsurface horizons of Brookston clay in Essex county (from G.C. Topp 1978).

similar (Table 14). Thus, surface layers of the right-of-way in Spread 1 had not only lower K_h and total porosities but also lower available water holding capacities than surface layers of adjacent undisturbed land.

Different water holding effects were noted for construction zones at a Haldimand clay site located on a 1977 oil pipeline right-of-way south of Hamilton. At this site both total (Fig. 7) and drainable (Fig. 8) porosities were reduced by about the same amount on the work area, implying little or no effect on water holding capacity. The effects of topsoil stripping of the right-of-way prior to construction were investigated at this site. Interestingly stripping did not appear to reduce compaction on the work area or over the trench.

Bulk density and K_h of cores from the surface layers of the Spread 4 Brighton sand site were measured. There was no effect on either of these parameters resulting from construction.

Penetrometer resistances (cone index) were significantly higher on the right-of-way than off at all Spread 1 sites in June 1978 and May 1979 (Table 14). Resistances averaged 67 and 50% more over the trench and on the work area respectively compared with adjacent undisturbed land. At site 2, Brookston volumetric moisture contents during penetration measurements in 1979 averaged 27.2, 29.9 and 36.9% in the 0-15 cm layer of the trench, work area, and undisturbed field respectively. From the water desorption curves, corresponding soil suctions were about 450, 350 and 80 cm of water on the trench, work area and undisturbed field respectively. Paul and DeVries (1979) obtained highly significant positive correlations between penetrometer resistance and soil water suction for a number of

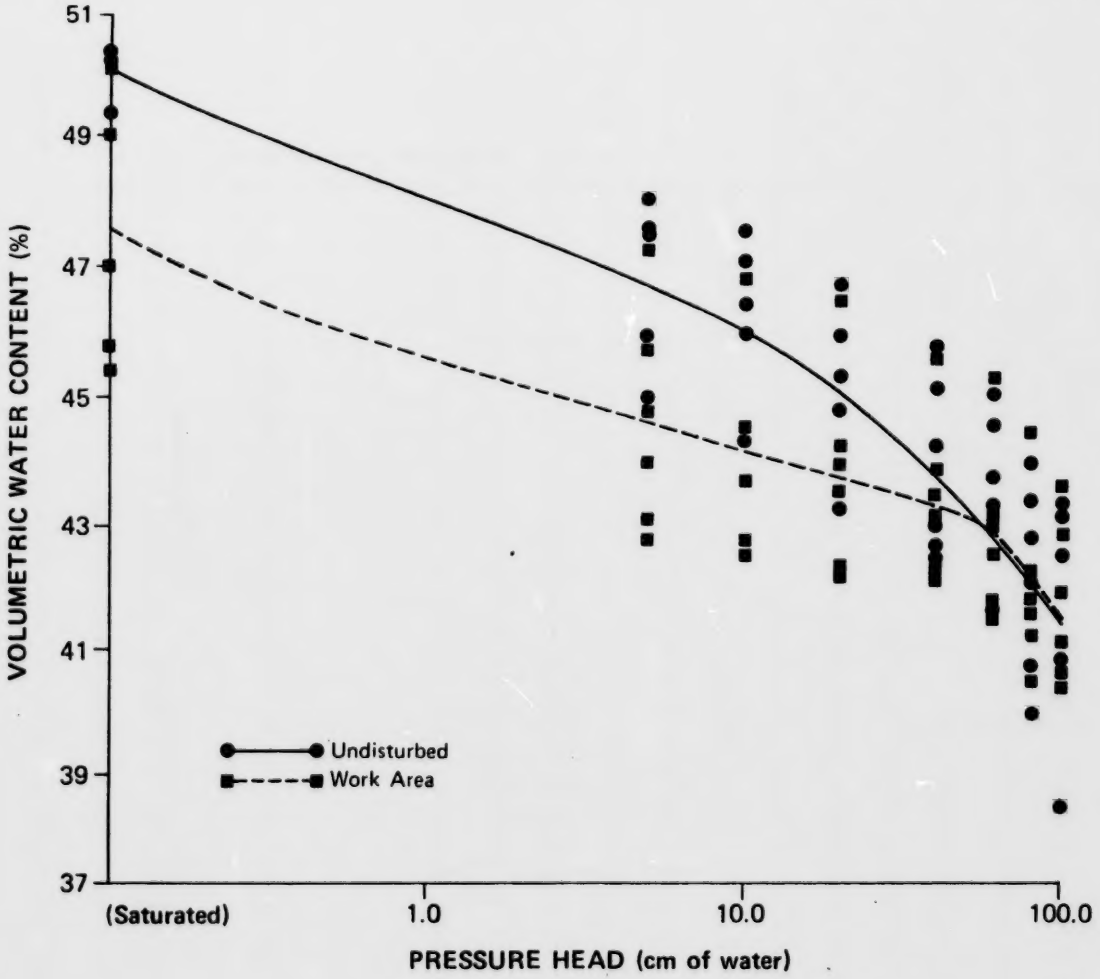

Fig. 7. Water desorption curves of surface layers of Haldimand clay on and off Hamilton-Nanticoke oil pipeline right-of-way.

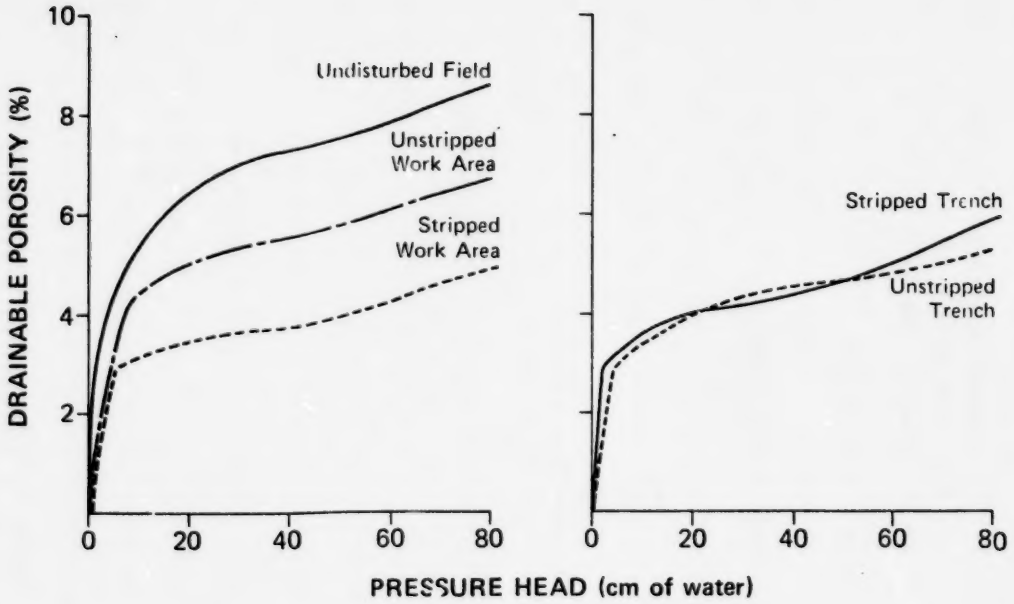

Fig. 8. Drainable porosity - pressure head relations of disturbed and undisturbed Haldimand clay.

soils. Thus, at least part of the observed differences in cone index across the construction zones may have been due to lower soil water suction pressures in undisturbed fields at sampling. Differences in soil strength as measured by the penetrometer may have affected soybean emergence at site 2, Brookston series. Soybean emergence rates (expressed as plants/m^2) were measured at this site in June 1978. Plant densities averaged 30.0, 29.0, and 36.0 plants/m^2 for the trench, work area and undisturbed field respectively. Differences in emergence rates between the field and right-of-way zones were noted on site 1 Brookston series, and sites 1 and 2 Perth series, but not on site 3 Brookston series.

Neither bulk density (Bd) nor saturated hydraulic conductivities (K_h) of the surface layers within construction zones of the spread 1 sites changed significantly between 1976 and 1977 (first and second years after construction). Maximum penetrometer pressures (C.I.) required to drive a 30^o cone to a depth of 15 cm in May 1979 were significantly lower than those in June 1978. This was due to higher soil moisture contents at sampling in 1979.

3.2 Response of Greenhouse Corn Grown on Right-of-Way Soils to N-P-K Fertilization

Some relevant chemical and physical properties of the fall and winter constructed North Gower silty clay and Morrisburg clay loam surface layers are presented in Table 15. Pipeline construction effects on these soils were similar to those observed at other sites. The undisturbed fall North Gower surface layer soil had a very high organic matter content which meant

Table 15. Chemical and physical properties of pipeline soils used to evaluate response of corn to fertilizer N, P and K

Soil series	Construction time	Zone	pH	C.E.C. (meq/100g)	Total N (%)	Soil Test P (ppm)	Soil Test K (ppm)	Silt (%)	Clay (%)	Plasticity Lower (water content w/w x 100)	Plasticity Upper (water content w/w x 100)
Morrisburg	Fall	Trench	7.8	24.3	0.19	14	94	38	24	32	43
		Work	7.8	18.7	0.24	11	82	36	24	30	40
		Field	7.8	26.5	0.28	14	82	38	25	37	50
Morrisburg	Winter	Trench	7.8	10.5	0.14	9	65	35	22	27	37
		Work	7.8	14.9	0.24	18	90	33	22	34	46
		Field	7.7	18.1	0.32	31	129	37	24	41	51
North Gower	Fall	Trench	7.8	23.0	0.11	7	321	40	53	27	53
		Work	7.6	24.5	0.11	6	278	43	52	28	53
		Field	6.9	56.2	0.73	13	172	37	50	57	81
North Gower	Winter	Trench	7.7	24.6	0.15	7	203	57	39	26	45
		Work	7.8	22.5	0.12	8	231	44	52	25	47
		Field	7.6	26.5	0.25	6	145	61	33	27	43

that top and subsoil mixing resulted in substantial reductions in C.E.C., total N and plasticity limits on the right-of-way.

Fertilization with N and P at 168 and 224 kg/ha respectively significantly affected ($p < 0.01$) dry matter vegetative corn yields on all four soils (Table 16). There was a less significant ($p < 0.05$) response to K (applied at 224 kg/ha) on the North Gower soils. Yields were also strongly affected by construction zone and there were significant zone - fertilizer interactions at all four sites.

3.2.1 Response to Nitrogen

Within each construction zone, fertilization with N increased yields significantly ($p < 0.01$) on all soils (Table 17). Yield increases due to N on fall-constructed Morrisburg soil were smaller on the right-of-way than off; the reverse was the case for winter-constructed Morrisburg. On the North Gower soils, yield responses due to added N were greater on right-of-way than off for both construction periods. Increases on the winter-constructed soils were considerably greater than those on fall constructed soils. The relatively high yields obtained without N fertilization on undisturbed North Gower-fall may have been due to its large pool of organic N. For all pots receiving N, corn yields from fall constructed right-of-way soils averaged 59% of undisturbed soils; for winter constructed right-of-way soils yields were 87% of undisturbed. Thus, greater responses to added N were noted on winter-constructed right-of-way soils.

Table 16. Analysis of variance tables for greenhouse-grown corn yields in which nitrogen, phosphorous and potassium as NH_4NO_3, $CaH_4(PO)_2$ and KCl were applied to 4 pipeline disturbed soils at rates 168, 224 and 224 kg/ha of N, P and K respectively.

Soil series	Construction time	Source of Variation (Calculated F Values)									
		Construction Zone		Fertilizer Effects							
		Undist Field vs right-of-way	Trench vs work area	N	P	K	NxP	NxK	PxK	NxPxK	Zone x Fert.
Morrisburg	Fall	272.9**	127.5**	329.4**	67.4**	0.34	26.18**	1.26	0.13	0.03	2.53**
Morrisburg	Winter	209.1**	51.9**	344.0**	27.3**	2.85	5.0*	3.85+	2.31	0.39	2.81**
North Gower	Fall	1467.6**	3.13+	592.0**	147.5**	6.39*	112.2**	1.18	10.81**	1.39	3.95**
North Gower	Winter	95.41**	51.34**	1500.0**	52.82**	5.76*	50.6**	1.12	0.51	0.30	5.72**

+ denotes significant effect at $p < 0.10$
* denotes significant effect at $p < 0.05$
** denotes significant effect at $p < 0.01$

Table 17. Corn yields and main effects resulting from applying N, P and K fertilizer at rates of 168, 224 and 224 kg/ha of N, P and K respectively to four pipeline-disturbed soils from Spread 6.

Construction zone	Dry Matter Yields — Main Effects Due To: N			P			K		
	-N	N	Difference	-P	P	Difference	-K	K	Difference
	(g/pot)			(g/pot)			(g/pot)		
Morrisburg - Fall-Construction									
Field	29.6	48.6	19.0**	38.0	40.1	2.1	39.0	39.2	0.2
Trench	9.9	25.5	15.5**	12.4	23.0	10.7**	17.4	18.7	1.3
Work	23.2	36.4	13.1**	25.4	34.2	8.8**	30.3	28.7	-1.6
Morrisburg - Winter Construction									
Field	42.4	57.9	15.5**	48.6	51.7	3.1+	48.9	51.4	2.4
Trench	19.1	41.4	22.3**	26.1	34.4	8.4**	29.0	31.4	2.4
Work	30.0	48.3	18.4**	37.0	41.3	4.3*	39.0	39.3	0.3
North Gower - Fall Construction									
Field	55.7	72.4	16.7**	59.9	68.1	8.2**	65.2	62.8	-2.5
Trench	11.3	36.7	25.4**	16.8	31.2	14.4**	25.7	22.4	-3.3+
Work	12.1	40.1	28.0**	19.9	32.3	12.4**	26.9	25.3	1.5
North Gower - Winter Construction									
Field	39.1	67.3	28.1**	47.3	59.1	11.7**	53.3	53.0	-0.3
Trench	26.2	68.5	42.3**	43.8	50.8	7.0**	49.7	45.	-4.7*
Work	17.0	60.5	43.5**	37.4	40.1	2.7	39.7	37.7	-2.0

+ denotes significant difference at $p < 0.10$
* denotes significant difference at $p < 0.05$
** denotes significant difference at $p < 0.01$

3.2.2 Response to Phosphorus

Yield responses to P fertilizer did not always reflect initial P soil test values. For example, significant responses ($p < 0.01$) were observed on fall Morrisburg trench soil, but not in adjacent undisturbed soil (Table 17) despite identical soil tests. On the other hand, yield increases on winter Morrisburg and fall North Gower soils followed expectations based on soil tests. North Gower winter soils on all zones were expected to respond to added P, but this only occured in the field and work area zones. As was the case with N, yields of treatments receiving P averaged less on fall constructed right-of-ways (59% of undisturbed) than on winter constructed soils (75%).

3.2.3 Response to Potassium

Responses to added K were non-significant on all Morrisburg zones (Table 17). Small, but significant yield reductions occurred on both North Gower trench soils when K was applied at 224 kg/ha of K.

3.2.4 Response to High N-P-K Fertilization

Yields of corn fertilized at 336,448 and 448 kg/ha of N, P, and K respectively confirmed observations at the lower fertilizer rate. Corn yields in fall constructed right-of-way soils averaged 70 and 72% of undisturbed (significantly lower at $p < 0.01$) for the Morrisburg and North Gower series respectively (Table 18). No significant construction zone yield reductions were apparent under winter construction. These results indicated that high N and P fertilization applications to these winter

Table 18. Yield of vegetative corn grown in pots on a till and lacustrine clay receiving the equivalent of 336 kg-N, 448 kg-P and 448 kg-K/ha

Soil Type	Construction timing	Yields (g/pot) Undisturbed soil	Trench	Work area
Morrisburg C.L.	Fall	65.1 a*	40.7 b	50.5 c
$\bar{S}\bar{x}$			1.2	
Morrisburg C.L.	Winter	62.2 a	63.8 a	64.6 a
$\bar{S}\bar{x}$			2.6	
North Gower C.	Fall	101.3 a	73.4 b	71.8 b
$\bar{S}\bar{x}$			2.8	
North Gower C.	Winter	94.7 a	88.2 a	89.5 a
$\bar{S}\bar{x}$			4.1	

* means within each row followed by the same letter are not different ($p<0.05$) according to Tukey's w procedure.

constructed right-of-way soils resulted in corn yields not substantially different from those grown on undisturbed soil. Increasing fertilization rates could not overcome yield reductions at the fall-constructed sites.

Over all fertility treatments, nitrogen concentrations in vegetative greenhouse-grown corn from both the Morrisburg and North Gower fall-constructed right-of-way soils were higher than those of corn grown in adjacent undisturbed soil (Table 19). No differences were observed across the Morrisburg winter zones, while slightly lower N concentrations were found in the winter North Gower right-of-way zones.

Potassium concentrations were consistently higher in corn grown on all right-of-way zones, indicating delayed maturity on the right-of-way (Ulrich and Hills 1967).

MacKenzie (1978a,b,c) conducted a field experiment at the same sites from which the soils used in this greenhouse study were collected (Table 20). Yield differences between zones were negligible for the North Gower winter site. Yields over the trench and on undisturbed land were not different at the Morrisburg winter site, but a significant reduction was apparent on the work area. Yields at the undisturbed North Gower fall site were very low and no meaningful comparisons could be made. These data indicate that yield reductions on winter (frozen ground) constructed right-of-way may be overcome by adequate fertilization programs, but that it is more difficult (or takes longer) to overcome yield reductions due to construction on wet, unfrozen ground.

Roots from one replicate of each treatment were separated from the soil, dried and weighed. Regression analysis produced a good relationship

Table 19. Average (over all fertility treatments) total nitrogen, phosphorous and potassium concentrations in vegetative corn grown in the greenhouse.

Soil series	Construction Period	Construction Zone	Nutrient Content N	P (%)	K
Morrisburg	Fall	Field	0.67	0.15	1.97
		Trench	0.79	0.13	3.92
		Work	0.82	0.15	2.52
		$S\bar{x}$	0.04	0.003	0.10
Morrisburg	Winter	Field	0.71	0.17	1.99
		Trench	0.74	0.16	2.68
		Work	0.72	0.16	2.16
		$S\bar{x}$	0.02	0.003	0.05
North Gower	Fall	Field	0.62	0.13	1.88
		Trench	0.73	0.14	5.52
		Work	0.69	0.15	5.08
		$S\bar{x}$	0.02	0.003	0.08
North Gower	Winter	Field	0.63	0.12	2.39
		Trench	0.55	0.14	4.22
		Work	0.58	0.14	4.74
		$S\bar{x}$	0.01	0.004	0.11

Table 20. Field plot silage corn yields fertilized with 224, 99 and 186 kg/ha of N, P, and K respectively.[1]

Construction zone	Yield (t/ha)			
	Morrisburg		North Gower	
	Winter	Fall	Winter	Fall
Undisturbed	10.3 (±1.55)	7.2 (±2.67)	7.2 (±0.94)	5.2 (±1.36)
Trench	10.0 (±1.03)	4.5 (±2.83)	7.6 (±2.01)	8.6 (±0.36)
Work	6.6 (±1.03)	4.8 (±1.26)	7.3 (±2.61)	8.1 (±0.56)

[1]Data courtesy of A.F. MacKenzie

between root and shoot yields (Fig. 9). These results provide some indication that observed yield reductions may have been due to soil structure degradation resulting from pipeline installation.

3.3 Effects of Topsoil and Subsoil Mixing on Yields

The effects of mixing surface (A horizon, 0-15 cm layer) and subsurface (B horizon, 20-40 cm layer) soil on greenhouse corn yields were investigated using previously undisturbed loam (Grenville series), silt loam (Castor) and a clay (Rideau). Total Kjeldahl N contents of the surface and subsurface layers were 0.122% and 0.056% respectively for Rideau, 0.318% and 0.055% for Grenville, and 0.164% and 0.013% for Castor. Five mixtures ranging from 100% to 0% topsoil were fertilized with 112 kg/ha of N, P and K.

Statistically significant positive correlations between dry matter corn yields and per cent topsoil existed for the Castor and Grenville series, but not for the Rideau (Fig. 10). For the Rideau, yields increased significantly between 100% and 50% subsoil, but declined slightly at 25 and 0% subsoil. Yields for 100% topsoil treatments were similar for the three soils despite considerable differences in surface soil N contents. Thus, TKN content can not be used as a soil test for available N. Total N uptake by corn was positively correlated ($p < 0.01$) to per cent topsoil for the three soils (Fig. 11). These results demonstrate the importance of the organic N pool in surface layer as a source of plant available N.

Slopes of N uptake by corn vs per cent topsoil for the three soils were strongly related to the original ratios of soil TKN in the surface and subsurface layers (Fig. 12). While soil TKN contents may not be generally related to

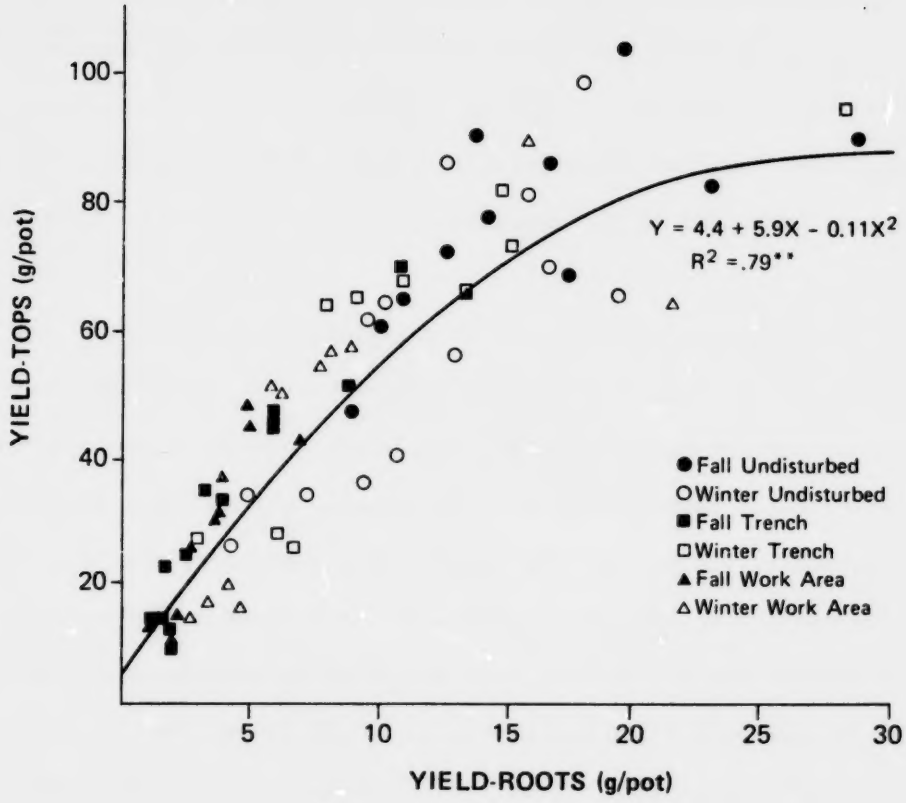

Fig. 9. Shoot and root weights of corn grown in North Gower and Morrisburg soils in the greenhouse.

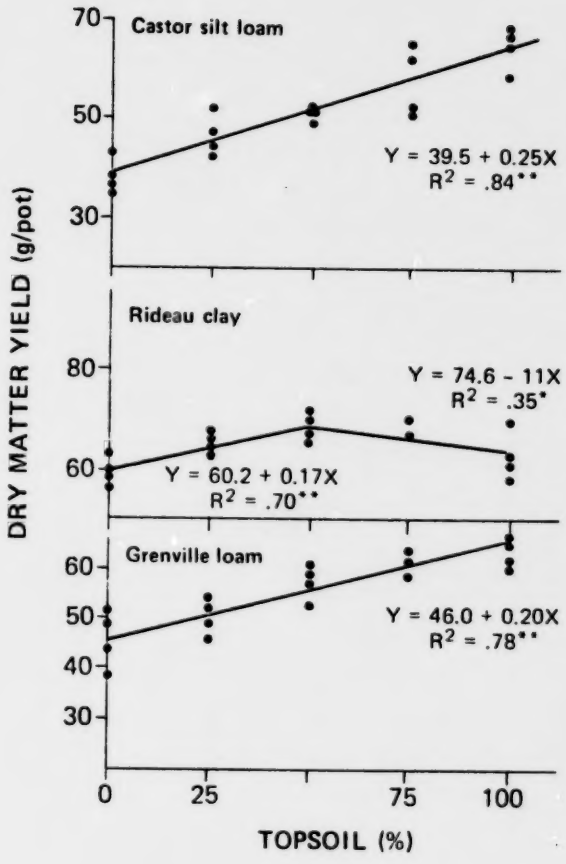

Fig. 10. Greenhouse grown corn yields as functions of percent topsoil in pots.

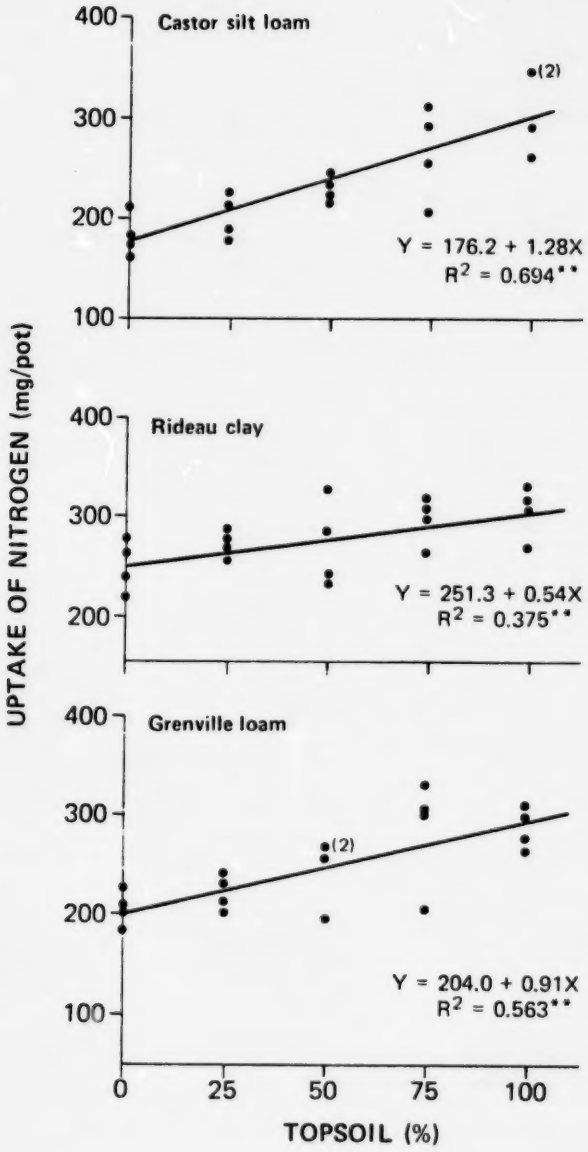

Fig. 11. Uptake of nitrogen by corn grown in the greenhouse with varying amounts of topsoil (and subsoil) and fertilized with 112 kg/ha of NH_4NO_3-N.

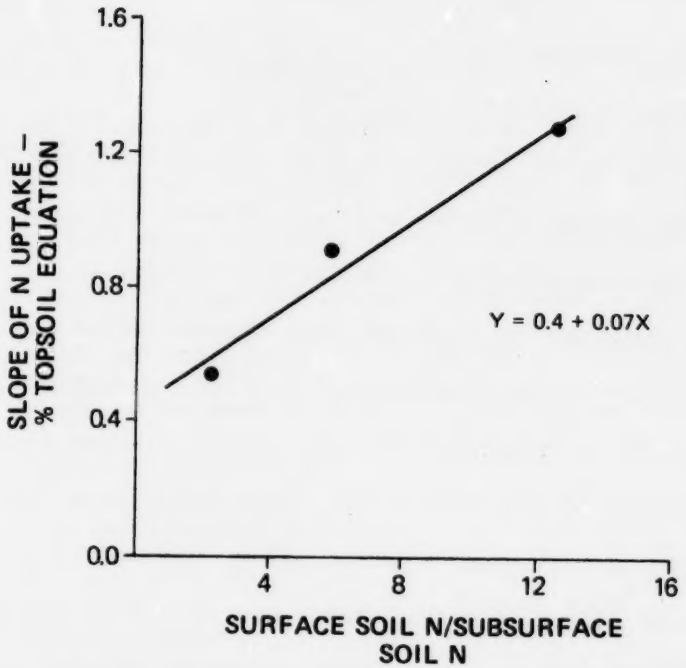

Fig. 12. Relation between slope of nitrogen uptake by corn (Fig. 11) and the ratio of total Kjeldahl nitrogen contents of surface and subsurface soil layers.

N uptake by corn, reductions in N uptake by corn caused by soil mixing for a soil type at a particular site may be related to changes in soil TKN. Bremner (1965) has suggested that between 1 and 3% of the organic N pool is mineralized during the growing season. Heavier than normally recommended N fertilization rates at least for corn appear to be justified at sites where significant mixing of topsoil and subsoil has occurred. Responses to fertilizer N by corn grown on A and B horizon soil mixtures were not evaluated, but the data suggest that a 50% dilution of topsoil with subsoil may warrant increasing recommended N fertilization rates for corn by 25-50%, assuming that the resultant soil TKN content is 50% of that of undiluted topsoil.

Soil organic matter levels must rise if soil N content is to increase. Research at the Central Experimental Farm, Ottawa, has shown that five large annual applications (about 30t/(ha·yr) on a dry weight basis) of dairy cattle liquid manure increased soil organic carbon content by about 0.7% in a sandy clay loam cropped to corn. Assuming a constant soil C:N ratio of 10, this organic C increase translates into a soil organic N increase of less than 0.10%. Thus heavy annual manure applications for a considerable period may be required to raise soil N levels in disturbed soils. Also, Russell (1973) has presented findings indicating that organic matter increases achieved by manure applications can be quite shortlived once treatments are stopped. The importance of preventing topsoil mixing with subsoil can not be overemphasized.

3.4 Susceptibility of Surface and Subsurface Soils to Compaction

Standard Proctor compaction curves for both surface (0-15 cm) and subsurface (20-40 cm) layers of Grenville loam, Castor silt loam and Rideau clay are plotted in Fig. 13. The shape of the Proctor curve has been explained by Baver et al. (1972). At low moisture contents (below the optimum for compaction), insufficient water is present to produce a lubrication effect between the particles, while at water contents in excess of the optimum, the incompressible nature of water results in a dilution of particle concentration.

Subsoils of both the Grenville and Castor Series could be packed to higher dry bulk densities at lower moisture contents than could the topsoils. On the other hand, Rideau clay topsoil packed to higher densities at lower water contents. Baver et al. (1972) and others have noted relationships between the lower plastic limit (PLAS) and optimum moisture content for compaction (OPTM) for many different soils. Data from more then 60 Quebec and Ontario soil horizons confirmed this relation:

$$OPTM = 3.2 + 0.78 \times PLAS \qquad R^2 = 0.53^{**}$$

For soil parent materials (C horizons)

$$OPTM = 0.3 + 1.00 \times PLAS \qquad R^2 = 0.64^{**}$$

Lower plastic limits of A, B and C horizons in this data set were strongly correlated ($p < 0.01$) with soil organic C contents. Both the lower and upper (liquid) plastic limits for these Québec and Ontario soil horizons could be predicted from knowledge of organic C and particle size distributions (Table 21). If a given soil profile contains a uniform particle size distribution, OPTM will be higher for the topsoil than for subsoil horizons.

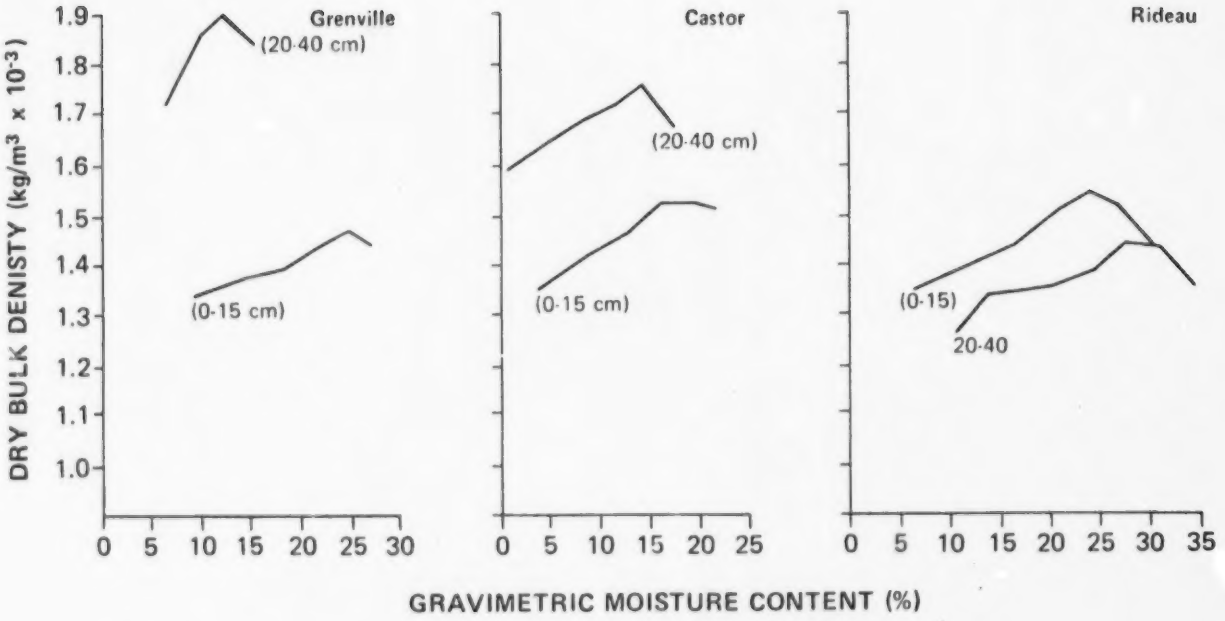

Fig. 13. Standard Proctor compaction curves for the surface and subsurface layers of soils used in greenhouse compaction experiment.

Table 21. Multiple linear regression equations relating some engineering properties of Quebec and Ontario soils of the Gleysolic, Luvisolic and Brunisolic groups to organic carbon contents and particle size distributions.[1]

Property	Units	Horizon	Regression Equation*	Reduction in Total sum of Squares (%)
Plastic Limit	grav. moisture (w/wx100)	A	$15.3 + 4.58\ X_1 + 0.137\ X_4$	57
		B	$21.8 + 5.86\ X_1 - 0.113\ X_2$	55
		C	$0.0 + 4.77\ X_1 + 0.068\ X_2 + 0.148\ X_3 + 0.238\ X_4$	80
Liquid Limit	grav. moisture (w/wx100)	A	$14.9 + 3.75\ X_1 + 0.593\ X_4$	73
		B	$7.0 + 5.55\ X_1 + 0.215\ X_3 + 0.535\ X_4$	63
		C	$0.5 + 0.303\ X_3 + 0.526\ X_4$	61
Optimum Moisture Content for Compaction (Proctor)	grav. moisture (w/wx100)	C	$-1.0 - 6.68\ X_1 + 0.192\ X_3 + 0.326\ X_4$	90
		A+B+C	$0.4 + 0.175\ X_3 + 0.271\ X_4$	79
Maximum Dry Density (Proctor)	g/cm^3	C	$0.003 + 0.143\ X_1 + 0.0221\ X_2 + 0.0155\ X_3 + 0.0125\ X_4$	95
		A B C	$0.040 + 0.0204\ X_2 + 0.0155\ X_3 + 0.0127\ X_4$	89

*X_1 - organic carbon (%)
X_2 - sand content (%)
X_3 - silt content (%)
X_4 - clay content (%)

[1]Data from CanSIS, Land Resource Research Institute, Agriculture Can.

Maximum dry densities (density at OPTM-Proctor) were particularly well related to sand content; densities could also be predicted from particle size distributions (Table 21). Thus, subsoils of lighter texture than the overlying topsoil will pack to higher densities at lower water contents than topsoils under a given compactive force. On the other hand, profiles with heavier textured subsoil than topsoils will respond to compactive forces as did the Rideau. Russell (1973) has pointed out that soil cultivation should be carried out at water contents equal to the lower plastic limit, but that cultivation at water contents much above this limit is liable to create a massive soil structure devoid of large pores.

Dry densities of surface and subsoils compacted under a pressure of 4.0 kg/cm^2 (about $\frac{1}{4}$ of the Standard Proctor), which was estimated to be the contact pressure exerted on soil by the rear tires of a fully loaded stringing truck used on the Sarnia-Montreal line, increased with water contents below the Proctor optimum for all horizons (Fig. 14). It is of note that the bulk density changes on Rideau clay resulting from 4.0 kg/cm^2 pressure corresponded with those observed on the Brookston and Perth right-of-way sites.

Raghavan et al. (1976) obtained statistical relationships between soil bulk densities under wheel tracks made by farm machinery and tire contact pressures, number of wheel passes and soil water contents. They found that soil densities under wheel tracks approached those of the standard Proctor as pressures and number of passes increased. Maximum density increases occurred at soil depths of 12-26 cm in clay and 20-30 cm in sand and sandy loam. If the bottom of the wheel truck was taken as the

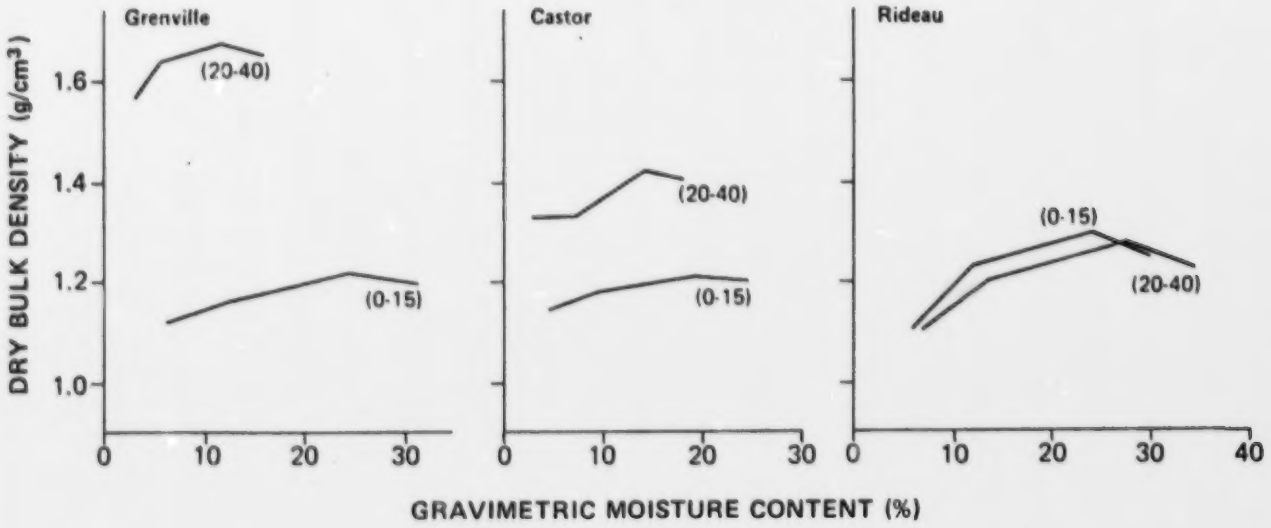

Fig. 14. Compaction curves for the surface (0–15 cm) and subsurface (20–40 cm) layers of soils compacted under a pressure of 4.0 kg/cm^2 at varying moisture contents.

0.0 depth reference maximum densities occurred at about a 10 cm depth in clay.

Rate of wheel slip affected soil structure properties very dramatically. Bulk densities increased by up to 0.4 g/cm^3 in sands and sandy loams and by about 0.2 g/cm^3 in a clay soil for wheel slippage rates of about 20%. Wheel slips of 20% or more in clay soils at water contents above the plastic, but below the liquid limit, caused very serious soil structure degradation resulting in reduced water permeability. Any machinery operating on wet (near the liquid limit) clay soils at high slip rates caused cement like consistencies at the soil surface. Slippage in excess of 30% usually resulted in complete failure of the soil causing deep rutting. Raghavan et al. suggested that machinery should be operated at slip rates of less than 5-8%.

These studies (Raghavan et al. 1976) which were carried out in Southern Quebec showed that compaction from vehicle traffic increased with soil moisture content below the plastic limit of the soil, but decreased at moisture contents in excess of the plastic limit. However, on heavy textured soils, at water contents in excess of the plastic limit, wheelslip was the predominant cause of degraded soil structure. These results were determined for off-road farm machinery with tire contact pressures ranging from 0.3 to 1.1 kg/cm^2. Wheel contact pressures for fully loaded stringing trucks for the Sarnia-Montreal line likely exceeded 3.0 kg/cm^2. Fuel trucks may also have contributed to compaction and rutting along the pipeline right-of-way.

3.5 Effects of Soil Compaction at Varying Soil Moisture Conditions on Corn Yields

A greenhouse experiment was undertaken to assess the impacts on vegetative corn yields resulting from compaction of Grenville, Castor and Rideau surface and subsoils at various soil moisture contents under a vertical compression pressure of 4.0 kg/cm^2 applied prior to seeding. Below the Proctor optimum moisture contents for compaction, yields of corn decreased with increasing soil moisture contents (during compaction) for surface Rideau and Grenville, but not Castor (Fig. 15).

In Castor silt loam, compaction of the surface layer resulted in more or less uniform and significant ($p < 0.05$) yield reductions of about 13% compared with uncompacted controls. Yields were not affected by the presence of compacted subsoil at a depth of 7.5 cm in the Grenville or Rideau soils. Corn roots grew down the sides of the pots after encountering packed subsoil. Yields were also not affected by the moisture contents at which Castor subsoil had been compacted prior to seeding although yields were significantly reduced (by about 17%) at all moisture contents (compared with controls). These results are noteworthy in that yield reductions were observed in clay, silt loam and loam soils with bulk densities ranging from 1.1-1.3 g/cm^3, a range often considered to be nonlimiting with respect to crop growth (Russell 1973). Similar results were obtained from the spread 1 field sites. Thus, compaction of medium to fine textured Ontario soils, which results in small bulk density increases, may cause significant reductions in agricultural productivity. Also, yield of corn grown

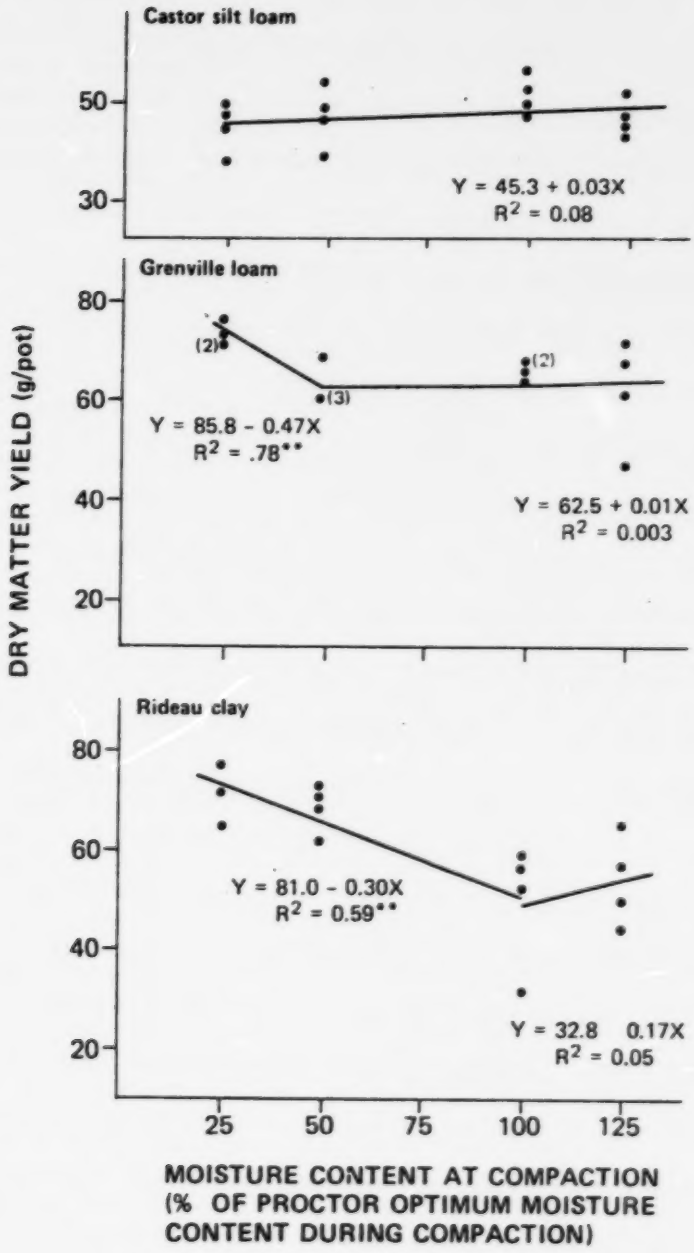

Fig. 15. Dry matter corn yields as a function of moisture content of surface soil layer during compaction under a pressure of 4.0 kg/cm^2.

on compacted Rideau clay tended to decrease as the soil moisture content during compaction increased.

3.6 Stripping of Topsoil

Mixing of topsoil and subsoil has been shown to adversely affect both chemical and physical properties of soil. Preservation of topsoil during pipeline construction has been strongly recommended (Shields 1980). An experiment was undertaken to evaluate actual topsoil conservation resulting from pre-construction stripping. It was performed on Haldimand clay during construction of the Nanticobe - Hamilton oil pipeline (fall 1977) under relatively good weather conditions and using commercial equipment. No special precautions were taken to preserve topsoil except that excess trench spoil was not spread across the right-of-way. The generally favourable weather conditions meant that no deep ruts were formed during disturbance.

Stripping resulted in somewhat better topsoil conservation over the trench, but had no impact on the work area (Table 22). Furthermore, stripping of topsoil from the work area may result in deeper compaction of susceptible subsoils, and in locations where subsurface drains exist increase the risk of damage to them. The results of this study indicate that spreading of excess trench spoil may adversely affect productivity across the entire affected area. The practice of spreading should be avoided, particularly in areas where subsoil presence at, or near, the surface will impede agricultural field operations.

Table 22. Soil organic and inorganic carbon contents at two adjacent sites, one of which had the 0-15 cm layer stripped prior to construction, along the 1977 Hamilton-Nanticoke oil pipeline right-of-way.

	Soil Depth (cm)	Carbon Content (%)				
		Trench		Work Area		Undisturbed
		Stripped	Unstripped	Stripped	Unstripped	
Inorganic	0-15	2.7	3.4	<0.1	<0.1	<0.1
	15-30	2.1	3.8	1.9	<0.1	<0.1
Organic	0-15	0.6	0.3	2.3	2.0	2.0
	15-30	0.4	<0.1	0.8	1.3	1.2

4. IMPLICATIONS FOR CONSTRUCTION PRATICES

The results of this study indicate that reductions in productivity on an Ontario oil pipeline right-of-way, constructed under somewhat wetter than normal conditions, were caused by soil mixing (topsoil with subsoil) and compaction. Soil mixing adversely affected fertility (chemical) and tilth (physical) properties. It is concluded that minimizing the impacts of pipeline installation requires preservation of topsoil. Stripping resulted in topsoil conservation over the trench, but had marginal impact on the work area. Results have indicated that much of the soil mixing on the work area was caused by spreading of trench spoil across the right-of-way. Avoidance of this practice may be more important in maintaining productivity of the work area than stripping topsoil.

Soil compactability studies indicated that subsoils are often more susceptible to compaction than topsoils, and that soils become more compactable as soil water contents increase below the lower plastic limit. Others have found that optimal compactability may occur at soil water contents at or near field capacity. Under wetter soil conditions, substantial soil structure degradation can result from shearing stresses resulting from tire slip. Wheel slip rates of about 5-8% have been proposed as acceptable. Thus, the minimum destruction of soil tilth should result if pipelining is carried out on dry soils (moisture contents about one half of field capacity). Such soil conditions are most likely to occur during June-September. Construction during this period is recommended.

Results of this study also indicate that construction in winter

when the soil is frozen may result in less damage to soil productivity than at other times provided an adequate fertility program is maintained. Average predicted monthly soil temperatures for various depths and locations in Quebec and Ontario are tabulated in Table 23. These predicted temperatures are thought to be good estimates for well drained cropland soils under "average" weather conditions (J.A. Shields, personal communication). Considerably less frost penetration is to be expected in poorly drained soils. The data suggest that adequate frost penetration to support machinery (20 cm) without snow removal to promote frost penetration occurs only in February west of London, in January and February between Kitchener and the Quebec border, and from January to March north of Montreal. Earlier frost penetration would occur if any snow were removed from the right-of-way, but this might require vehicle traffic across wet, unfrozen ground. Soil temperature data for other locations throughout Canada may be found in Ouellet et al. (1975).

Some of the more common problems which occur in pipeline construction together with recommended mitigative measures are summarized in the appendix. These measures were compiled by the staff of the Land Resource Research Institute.

Table 23. Estimated monthly normals of soil temperature at various locations in Ontario and Quebec[1]

Location	Soil Temperature (°C)											
	Dec.			Jan.			Feb.			March		
Depth (cm)	10	20	50	10	20	50	10	20	50	10	20	50
Sarnia	1.9	2.7	4.2	0.0	0.5	2.0	-0.3	0.0	1.2	1.0	0.9	1.5
London	1.6	2.4	3.7	0.1	0.4	1.9	-0.4	-0.1	1.1	0.7	0.7	1.3
Kitchener	1.1	2.1	3.5	-0.6	0.0	1.4	-0.9	-0.5	0.6	0.4	0.3	0.8
Guelph	0.8	1.7	3.2	-0.7	-0.3	1.3	-1.0	-0.7	0.5	0.3	0.2	0.8
Toronto Airport	1.1	1.9	3.5	-0.5	-0.1	1.5	-0.8	-0.5	0.8	0.7	0.6	1.2
Belleville	1.0	1.6	3.2	-0.3	0.0	1.4	-0.6	-0.4	0.9	0.9	0.8	1.4
Kingston	1.1	1.9	3.3	-0.3	0.0	1.5	-0.8	-0.5	0.8	0.5	0.5	1.1
Morrisburg	0.8	1.4	2.8	-0.7	-0.6	1.2	-0.8	-0.7	0.8	0.3	0.2	0.9
St. Jerome	0.2	1.1	2.2	-0.7	-0.5	0.9	-0.6	-0.4	0.7	0.0	0.1	0.7

[1]Data from Ouellet et al. (1975)

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APPENDIX

SUGGESTED LAND MITIGATION MEASURES FOR PIPELINES *

Land Condition	Problems	Recommended Land Mitigation Measures
L.C.I. BEDROCK WITHIN 7 FEET OF SURFACE		
1.1 Soil 1-7 feet deep over bedrock	(a) Migration of topsoil into underlying aggregate fill can decrease proportion of topsoil in surface layer resulting in moisture and fertility problems.	(a) Maintain at least 18 inches of graded backfill between topsoil and aggregate fill. Final thickness of topsoil and graded backfill should be at least 24 inches to allow for cultural practices and plant growth.
	(b) Shot rock or bedrock fragments added to topsoil during pipeline operations. Potential hazard to machinery and grazing animals.	(b) i) During rock-blasting operations, carefully cover the rock with good quality matting to minimize dispersion of blasted rock fragments. ii) Keep topsoil spoil pile as far as possible from trench. Remove rock fragments down to 2 inch size, if possible, from topsoil after blasting.
1.2 Soil less than 1 foot deep over bedrock.	Revegetation problems due to topsoil loss or dilution by rock fragments.	i) Follow measures 1.1a and 1.1b above. ii) Stabilize topsoil on right-of-way to prevent soil erosion.
1.3 Sloping trench in bedrock	Downslope seepage or wet spots from water channeled by trench.	i) Leave rock plugs in open trench until pipe is laid. ii) Consider trench dams made from sandbags, concrete, etc. after pipe is laid. iii) Install drainage tile to drain wet spots.

* compiled by the staff of Land Resource Research Institute. Measures are based on observations made during construction of the Sarnia-Montreal oil pipeline. They are presented as suggested measures; new technology may have reduced some of the potential problems, thus affecting mitigative measures.

Land Condition	Problems	Recommended Land Mitigation Measures
L.C.2. CONTRASTING SOIL MATERIALS		
2.1 Layers of cobbles or stones at depth	Addition of cobbles or stones to topsoil and upper subsoil can result in problems of tillage, fertility and moisture-holding capacity.	Remove all introduced stones and cobbles, down to 2 inch size if possible, from the upper 18 inches of soil, across the width of the easement, and those added to the soil surface beyond the easement by blasting or trucking operstions. Ideally, topsoil, similar subsoil and dissimilar subsoil should be stockpiled separately, then backfilled over pipe in their original sequence. Alternatively, if the topsoil and upper subsoil have similar textures, they could be removed and stockpiled separately, away from the lower subsoil. This would, of course, dilute the topsoil and special practices would be necessary to rebuild depleted organic matter and plant nutrients.
2.2* Fine soils over coarse soils, e.g. loam to clay over sand or gravelly sand	If the topsoil texture and structure are markedly different from those of the upper subsoil, moisture, fertility, plant growth or tillage problems may occur.	
2.3* Coarse soils over fine soils, e.g. sand to gravelly sand over loam to clay		
* Applies only at owner's request for special crops such as sod, turnips, etc.		

Land Condition	Problems	Recommended Land Mitigation Measures
L.C.3. SURFACE WATER PROBLEM SITUATIONS (usually during spring and fall when run-off and water tables are highest)		
3.1 Ponding in depressions and drainage runs.	Excess water softens and weakens the bearing capacity of the soil, causing mud holes to develop with traffic. As traffic is diverted around, the holes may widen until damage is done beyond the right-of-way.	i) If the ponded area is so extensive that it cannot be punped or drained then work should be delayed until drier conditions prevail. If possible, leave excavation and pipe-laying in the worst areas to special "tie-up" crews after control measures are approved. ii) Remove surface water by pumping from depressed areas. iii) Use drainage culverts and ditches to control surface waters.
3.2 Standing water in trench	Softening and erosion of trench sidewalls followed by sidewall caving and trench widen'ng. This neces-sitates re-excavation of trench by dragline before pipe is laid, re-sulting in additional trafficking on right-of-way and frequent contami-nation of topsoil spoil pil by re-excavated materials.	i) Do not leave trench open more than 3 days from ditching to backfilling. Where high water tables occur, or rain is forecast, the trench should be open less than 3 days. ii) Pump water from trench before laying pipe and backfilling.
3.3 Sloping trench in soil	Downslope seepage or wet spots due to channeling of water by trench. Especially serious where water channelled from saline to non-saline area.	i) Leave earth plugs in open trench on slopes greater than 5 percent, until pipe is laid. ii) Install trench dams of sandbags, concrete, etc., after pipe is laid. iii) Install drainage tile to drain surface seepage or wet spots along the slope.
3.4 Surface drainage disruption	Ponding or disruption of surface water flow by surficial trench features such as berms or subsidence.	Restore former surface contours by flatening berm or blading in subsided areas if necessary.

Land Condition	Problems	Recommended Land Mitigation Measures
L.C.4. GROUND WATER PROBLEM SITUATIONS		
4.1 Silts and sands below the water table	Progressive failure of trench caused by sand flow may affect right-of-way and even land beyond this, if remedial action is not taken soon enough. The exact location of such areas if often difficult to predict from available soil survey information.	i) Treat such areas like highway crossings i.e. leave excavation to specialist "tie-up" crews after control measures approved. ii) Control measures could include a) Installing a thin casing during excavation. b) Use of ground water control e.g. well pointing for severe cases.
4.2 Disruption of drainage tile	Disruption of tile drainage by silting, broken or collapsed tiles, capping tiles too long.	i) Cap tiles along trench until replacement tile is inserted across trench. This should be done as speedily as possible to minimize disruption. ii) Check all tile lines across right-of-way, after pipe is laid, for collapsed tiles due to heavy machinery pressures. iii) The top of the pipe should be at least 4 feet below the ground surface both in land which is drained and in land which may be drained in future.

Land Condition	Problems	Recommended Land Mitigation Measures
L.C.5. SEVERE RUTTING SITUATIONS UNDER WET CONDITIONS	Under wet conditions the soil strength is reduced. Trafficking on cultivated soils (or even on grassed soils) may locally exceed the bearing capacity, and rutting develops. Soil compaction, ponding and mixing of subsoil with topsoil are some adverse effects of rutting.	i) Before the trench is excavated seriously consider routing the stringing trucks over the proposed trench area to lay the pipe. ii) Ideally, construction should be stopped when the soil is very moist or saturated. Sufficient damage is being done to soils, when ruts deeper than 3 inches are formed over a length of 50 feet, to warrant delaying construction until the ground is drier or frozen. iii) Load-spreading mats could be used to spread the load, provided they didn't aggravate the damage. They could be used on narrow, wet areas such as natural drainage ways. This would eliminate the greatest cause of rutting damage to the right-of-way.

Land Condition	Problems	Recommended Land Mitigation Measures
L.C.6. COMPACTION UNDER MOIST TO WET CONDITIONS	Under moist to wet conditions the soil strength is reduced. Soil structures are then more susceptible to damage by trafficking. Such damage compacts the primary and secondary structures, thereby reducing the porosity. This, in turn restricts air and water movement through the soil, limiting root growth and transfer of nutirents. The condition may not be noticeable on the right-of-way if the compaction occurs on moist soil and is not accompanied by rutting.	i) Before the trench is excavated seriously consider routing the stringing trucks over the proposed trench area to lay the pipe. This would confine the worst compaction damage to the trench area, where subsequent excavation would assist renovation by breaking up compacted layers. ii) The most practical measure is to stop operations on susceptible soils if they are moist to wet, and delay construction until more suitable conditions prevail. iii) Structural damage will not be completely remedied by chisel ploughing at the time of renovation, especially if the soils are very moist or wet. Improvements in structure may require several cycles of freeze-thaw and applications of green and farm yard manures.

Land Conditions	Problems	Recommended Land Mitigation Measures
L.C.7. SOIL EROSION	(a) Water erosion of all sloping soils except coarse sands. After renovation bare topsoil on land with slopes greater than 2% is susceptible to erosion until it is stabilized by vegetation. The potential for erosion damage will be greater if there are linear features such as tracks, ruts, etc., on the right-of-way, that could channel water down the slopes. Also soil compaction and structural degradation caused by heavy machinery can decrease infiltration, increase surface puddling, etc., and intensify soil erosion.	i) Revegetate all bare slopes as soon as possible Until vegetation is established try to stabilize soils on bare slopes by eliminating linear features and soil compaction as much as possible. Erosion control methods should be followed such as cross-slope cultivation, contouring, terracing, mulch covers, straw savers, etc. ii) Slopes should be seeded down to well-fertilized, rapidly growing cover crops. Consider the use of adaptable legumes like birdsfoot trefoil or crown vetch to provide nitrogen to the soil.
	(b) Wind erosion, particularly on dry, sandy and silty soils. In Western Canada wind erosion can be a threat on summer fallow fields of any soil texture during periods of drought. Once wind erosion of soil commences on the easement, it may spread across adjacent fields.	i) In susceptible areas, consider bringing the stringing trucks over the trench area before trench excavation. This would restrict their pulverizing of surface structure to the trench area. ii) In susceptible areas, limit travel of equipment and vehicles along easement, if wind erosion is initiated by soil pulverization. If necessary, prohibit travel until moister soil conditions return.

Land Conditions	Problems	Recommended Land Mitigation Measures
L.C.8. ORGANIC SOILS location is predictable from soil survey information.	Water tables are typically high; bearing strength is low. After back-filling, soils in areas that have been drained will subside at an accelerated rate.	i) If possible, realign pipeline to avoid such areas. ii) If organic soil is shallow, deepen trench to install pipeline in underlying mineral soil. iii) Spread the load over as wide an area as possible i.e. use corduroy in uncultivated areas. iv) Ensure that water table will resume its previous elevation.

Land Conditions	Problems	Recommended Land Mitigation Measures
L.C.9. TOPSOIL LOSS	(a) Topsoil incompletely stripped from trench area.	(a) Remove and stockpile all topsoil to a maximum depth of 12 inches from above the trench.
	(b) Topsoil spoil piles contaminated by subsoil and rock.	(b) Do not overlap topsoil and subsoil spoil piles. At road corssings, where trench enlargement usually results in wider subsoil spoil piles, locate the topsoil spoil piles farther from the trench to avoid subsoil contamination. Try to prevent trench materials from beind dumped on the topsoil spoil piles during "clamming" operations.
	(c) Topsoil underneath subsoil spoil pile contaminated by subsoil.	(c) Strip topsoil from areas that will be overlain by subsoil spoil piles.
	(d) Topsoil on right-of-way contaminated by subsoil from rutting and tile drain excavations and by shot fragments from rock blasting.	(d) Take precautions against rutting and shot rock contamination of topsoil on right-of-way and in spoil piles. Strip and stockpile topsoil during trenching across right-of-way for tile drain repairs.
	(e) Thin topsoil over trench and stringing area after renovation.	(e) Subsoil spoil in excess of that required to backfill the trench and construct an adequate berm should not be spread over the right-of-way but should be removed to an acceptable disposal site. The topsoil should be replaced and evenly spread by equipment smaller than D9 bulldozer. Topsoil thickness over the trench, after renovation, should be no less than 3/4 then thickness of topsoil in fields adjavent to the easement.